Moonbows Over Yosemite

Predicting Moonbows in Lower Yosemite Falls

HONORS THESIS

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ABSTRACT

Most people have seen a rainbow following a spring shower or in their garden hose, but few have witnessed the spectacular beauty of a lunar rainbow, or moonbow. One location where the appearance of moonbows is a well-documented occurrence is Lower Yosemite Fall, Yosemite National Park, California. Photographers travel to see this rare event, but with the vague guidelines given by the park's resources photographers have been disappointed by the absence of a moonbow on full-moon nights. For this reason, we created a computer program that would help us to predict the precise dates and times when moonbows would be visible in Lower Yosemite Fall. We developed six conditions that were necessary for moonbows to be visible in the waterfall for viewers at the viewing area at the base of the falls:

(1) Clear Skies
(2) Abundant Mist and Spray at the Base of the Fall
(3) Dark Skies
(4) Bright Moonlight
(5) Moonlight Not Blocked by Mountains or Cliffs
(6) Correct Rainbow Geometry

Precisely defining these conditions required visiting the park in order to make our own measurements, and calculations in spherical trigonometry were carried out in order to develop practical equations. We have successfully written this computer program, published the results in a variety of locations where photographers can utilize them, and predicted when moonbows would occur in Lower Yosemite Fall for 2006, 2007 and 2008.

INTRODUCTION

After a spring downpour, many have been inspired by the sight of a late afternoon rainbow in the eastern sky. Even before it appears, you sense that it might and you keep a lookout. Maybe you once fancied finding a pot of gold where the colorful arc ends.

Yet how many of us have seen a rainbow at night? While this is a fairly rare event, nature lovers as far back as Aristotle knew it was possible for a bright Moon, like the Sun, to produce a rainbow.

> "The rainbow occurs by day, and it was formerly thought that it never appeared by night as a moon rainbow. This opinion was due to the rarity of the phenomenon: it was not observed, for though it does happen, it does so rarely… The colors are not easy to see in the dark… The moon rainbow appears white…" (Aristotle, Meteorologica, circa 340 B.C.)

Physics Behind the Rainbow

Rainbows are produced by rays of light from the Sun (or Moon) shining on spherical drops of water. The combination of refraction, internal reflection, and dispersion produce the display. The primary bow forms a circular arc of radius of 42° with blue on the interior and red on the exterior of the arc. The primary bow is created by two refractions and one internal reflection as shown in Figure 1. Under good conditions – abundant water drops, clear air and bright sunlight – a much fainter secondary rainbow can appear with a radius of 51° and with the sequence of colors reversed.

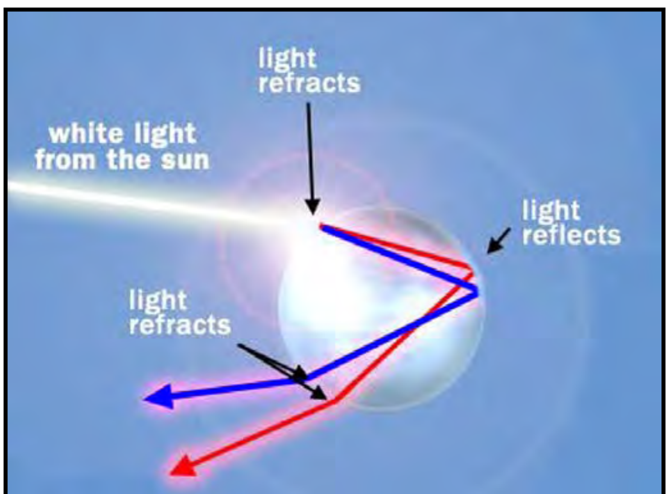


Figure 1: Diagram of light's path through a spherical water droplet.

The center of the rainbow is the point directly opposite the Sun, the antisolar point. The antisolar point is located as far below the horizon as the Sun is above the opposite horizon and is easily recognizable because it is marked by the shadow of your head.

At night the geometry is the same except that the antilunar point (opposite the Moon) is the center for this display – known as a lunar rainbow, moon rainbow, or moonbow. The human eye loses most of its color sensitivity in dim light, and visual observers usually describe moonbows as gray, white, or silver.

Confirming this fact, Marcel Minnaert, a pioneering authority on atmospheric optics likewise pointed out that:

> "… moon-rainbows are naturally very weak. That is why they can be seen practically only when the moon is full and why they are seldom coloured, just as feebly illuminated objects usually appear colour less at night. "
>
> (Marcel Minnaert, The Nature of Light & Colour in the Open Air, 1954)

But under ideal conditions – bright moonlight from a full or nearly-full Moon, clear air, and abundant water drops – some people have reported seeing the colors in lunar rainbows.

Mark Twain and Moonbows

Mark Twain records just such an observation, made in 1866 during a trip to the Big Island of Hawaii:

> "Why did not captain Cook have taste enough to call his great discovery the Rainbow Islands? These charming spectacles are present to you at every turn; they are common in all the islands; they are visible every day, and frequently at night also – not the silvery bow we see once in an age in the States, by moonlight but barred with all bright and beautiful colors, like the children of the sun and rain. I saw one of them a few nights ago."

(Mark Twain, Roughing It, Chapter LXXI)

While returning by ship from Hawaii to San Francisco, Twain made a similar report in his journal of a "splendidly-colored lunar rainbow" on July 27, 1866.

Thirteen years later the celebrated author was returning to America from a European tour and again experienced near-ideal conditions:

> "Aug. 31 – At sea in the "Gallia," approaching New York – about 9 PM brilliant moon, a calm sea, & a magnificent lunar rainbow – a complete arch, the colors part of the time as brilliant as if it were noonday – some said not quite as brilliant, softened with a degree of vagueness, but to me it was not different from a daylight rainbow."
>
> (Mark Twain, notebook entry, August 31, 1879)

Mark Twain considered himself lucky to see this rare lunar phenomenon multiple times in his life. However, Mark Twain was not the only historical figure to have seen these wonders.

Moonbows at Sea: Ben Franklin

Another observer of a lunar rainbow at sea was none other than the young Benjamin Franklin, on a return voyage from London to Philadelphia in 1726:

> "Contrary wind still. This evening the moon being near full, as she rose after eight o'clock, there appeared a rainbow in a western cloud to windward of us. The first time I ever saw a rainbow in the night caused by the moon."
>
> (1726 August 30 [Julian calendar] = September 10 [Gregorian calendar], journal of Benjamin Franklin)

Franklin's journal for this trip holds much of interest to astronomers. In addition to seeing a lunar rainbow, Franklin also recorded witnessing a solar eclipse (1726 September 14 [Julian] =

September 25 [Gregorian]) and then, just over two weeks later, a partial lunar eclipse (1726 September 30 [Julian] = October 11 [Gregorian]).

Moonbows in Waterfalls

One never knows when he or she will see a rain shower on a moonlit night. So they can travel to a more reliable place on a moonlit night, the spray near waterfalls. Going to a waterfall at the right time of year assures that at least one of the criteria necessary to form a moonbow, abundant water droplets, will be met. The occurrence of lunar rainbows in the mist near waterfalls has been enjoyed by tourist at several well known locations. At Victoria Falls, on the border between Zambia and Zimbabwe, tour companies offer "Lunar Rainbow Tours." Moonbow observing is also a popular activity at Cumberland Falls in Kentucky, and early postcards show that the hotel adjacent to the falls was named the "Moonbow Inn." Lunar bows were a great tourist attraction at Niagara Falls in the mid 1800s, and the phenomenon gave its name to two topographic features just south west of the American Falls:

> "The name Luna Island and Luna Falls comes from the fact that the light of a full or nearly full moon creates a lunar rainbow in the mist. Most visitors never see it, however, for in summer the falls are lit by artificial light until well after midnight."
> (New York Times, June 1988)

Yosemite Moonbows: John Muir

One of the first modern preservationists, John Muir, wrote numerous letters, essays, and books telling of his adventures in nature which strongly influenced the formation of the modern environmental movement. His direct activism helped to save Yosemite Valley and founded the Sierra Club which is one of the most important conservation organizations in the United States. So it is no surprise that Muir described in great detail the occurrence of moonbows in the waterfalls of Yosemite Valley:

> "Lunar rainbows or spray-bows also abound in the glorious affluence of dashing, rejoicing, hurrahing, enthusiastic spring floods, their colors are distinct as those of the

sun and regularly and obviously banded, though less vivid. Fine specimens may be found any night at the foot of the Upper Yosemite Fall, glowing gloriously amid the gloomy shadows and thundering waters, whenever there is plenty of moonlight and spray. Even the secondary bow is at times distinctly visible. " (John Muir, The Yosemite, 1912)

While exploring the valley at night in search of a moonbow, as he often urged visitors to Yosemite Valley to do, Muir made his way from the Upper Yosemite Fall along the edge of a the gorge in order to see the moonbows forming in the lower falls. In his 1912 book *The Yosemite* he wrote:

> "And down in the exceedingly black, pit-like portions of the gorge, at the foot of the highest of the intermediate falls, into which the moon beams were pouring through a narrow opening, I saw a well-defined spray-bow, beautifully distinct in colors, spanning the pit from side to side, while pure white foam-waves beneath the beautiful bow were constantly springing up out of the dark into the moonlight like dancing ghosts…"
> (John Muir, The Yosemite, 1912)

In an 1871 letter to long time friend, Mrs. Ezra S. Carr, Muir described another double lunar bow:

> "… that you could be here to mingle in this night-noon glory! [I] am in the upper Yosemite Falls… In the afternoon I came up the mountain here with a blanket and a piece of bread to spend the night … Silver from the moon illumines this glorious creation which we term 'falls,' and has laid a magnificent double prismatic bow at its base. The tissue of the fall is delicately filmed on the outside like the substance of spent clouds, and the stars shine dimly through it."
> (letter from John Muir to Mrs. Ezra S. Carr, circa April 3rd, 1871)

After reading Muir's dramatic accounts, the idea of writing a computer program to predict dates and precise times when moonbows would appear in Lower Yosemite Fall was first hatched. However, moonbows are the most impressive when all colors are visible to the viewer.

The retina of the human eye contains two types of photoreceptors, rods and cones. Rods are more numerous and sensitive than cones, but they are not sensitive to color. Daylight vision is primarily cone vision. However, vision at night is primarily rod vision and therefore colors are only perceptible to very sensitive eyes. Since most people would only see a light silvery bow, how could we assure that everyone would enjoy the same awe inspiring display that John Muir's sensitive eyes were able to witness?

With modern advances in photography techniques and equipment, it is easy for even amateur photographers to capture the full palette of colors present in lunar rainbows. It is common practice to slow the shutter speed of the camera in order to allow more light to reach the film (or digital camera chip) of the camera when taking pictures at night. This technique called time-exposure photography and has resulted in many amazing photographs of night landscapes and particularly moonbows.

The Missing Moonbow in 2005

The existing Yosemite guide books give only some very general advice about seeing and photographing moonbows, informing visitors to try near the time of full Moon and to stand with the Moon at your back and the falls in front of you.

While searching for moonbow-related messages in the archive of a nature photography discussion group (Calphoto at Yahoo), we ran across an incident that made us realize how useful precise computer predictions might be. Following the guidelines of the Yosemite visitors' books, on the evening of June 22, 2005, there was a nearly full Moon so about 50 photographers gathered at the viewing area near the base of Lower Yosemite Fall. The temperature began to drop as the evening wore on and the mist blown down from the waterfall kept the photographers uncomfortably wet. By midnight the group members dispersed wondering why the moonbow had failed to appear when "all obvious conditions were in place."

Preliminary analysis revealed that on June 22, 2005 the Moon rose with a large southern declination (-28 degrees). This declination would cause the moonrise to be delayed above the local horizon. We wondered if we could produce a more precise explanation from a detailed computer analysis for Lower Yosemite Fall.

COMPUTER PROGRAM

In order for a moonbow to be readily visible, six conditions must be simultaneously satisfied. The first two conditions are weather-dependent, but the last four astronomical conditions can be modeled by a computer program.

Six Conditions for a Moonbow to Appear

(7) Clear Skies
(8) Abundant Mist and Spray at the Base of the Fall
(9) Dark Skies
(10) Bright Moonlight
(11) Moonlight Not Blocked by Mountains or Cliffs
(12) Correct Rainbow Geometry

Clear Skies

For obvious reasons, a sky free of cloud cover over the Moon is necessary to allow the moonlight to reach the mist created by the waterfall. This is not possible to calculate in a long term program and is thus left up to the viewer to check weather forecasts regarding whether the sky will be clear on the night that they visit the fall.

Abundant Mist and Spray at the Base of the Fall

The best moonbow dates fall in the snowmelt runoff season, at Yosemite typically extending through April, May, June, and sometimes early July. The height of the snow pack and the rate at which the pack melts varies from year to year. These factors can affect our results for when moonbows will occur because a year with a lot of runoff will create a denser mist and thus allow moonbows to be visible for a Moon that is slightly less illuminated to produce a moonbow. On the other hand if the snowmelt occurs very rapidly, moonbows will not be visible in July.

Dark Skies

Twilight is a common term, but few realize that there are three types of twilight – civil, nautical, and astronomical twilight.

Civil twilight occurs when the center of the Sun is between the horizon and 6 degrees below the horizon. The brightest stars appear during civil twilight and there is enough light from the Sun that no artificial sources of light are necessary to carry on outdoor activities.

Nautical twilight is the term for when the center of the Sun is more than 6 degrees but no more than 12 degrees below the horizon. This twilight is named for the time sailors could take reliable star sights of well known directional stars using a visible horizon for reference. During this time general outlines of ground objects may be distinguishable but detailed outdoor operations are not possible and the horizon is indistinct.

Astronomical twilight is defined as the time when the center of the Sun is more than 12 degrees below the horizon but less than 18 degrees. Most observers would consider the entire sky already fully dark even when astronomical twilight is just beginning but the faintest stars and diffuse objects, such as nebulae and galaxies, can only be best observed beyond the limit of astronomical twilight.

We chose to use the middle of nautical twilight as the start time for considering moonbows possible in our program. Information on the location, azimuth and altitude, of the Sun is gathered from the Jet Propulsion Laboratory Horizons system. Our computer program rejects times until after the middle of nautical twilight, so that the Sun's altitude is more than 9 degrees below the horizon. It is possible for a moonbow to be visible before the Sun is 9 degrees below the horizon if the mist is dense enough and this possibility is noted in our results.

Bright Moonlight

For any given date and time, our program calculates the brightness of moonlight as a function of four factors – lunar phase law, lunar distance, solar distance, and atmospheric extinction. Each of these effects on the brightness of moonlight has a corresponding equation which is found in Astronomical Algorithms by Jean Meeus and is used in our moonbows' computer program.

Most important is the phase of the Moon and the lunar phase law for luminosity.
What follows is the equation for lunar phase law where α is the phase angle of the moon in degrees:

$F_1 = 10^{-0.4*\Delta m}$ where $\Delta m = 0.026\,|\alpha| + 4*10^{-9}\,\alpha^4$

And if $|\alpha| < 7^\circ$ then $F_1 = F_1 * (1.35 - 0.05\,|\alpha|)$

The second portion of this law is referred to as the opposition effect which is the brightening of the moon (and several other heavenly bodies) when illuminated from directly behind. This is a difficult behavior to model because when the Sun moves directly behind the Earth, we observe a lunar eclipse. Therefore at the point that we expect the Moon to be brightest, we actually have no light visible from the Moon.

The second factor is the altitude of the Moon, with a Moon high in the sky appearing much brighter, while a Moon close to the horizon appears much fainter as it light passes through more atmosphere. We call this atmospheric extinction and it is mathematically expressed as follows:

$$F_2 = 10^{-0.4*k[(airmass)-(airmass)ref]}$$

where $Airmass = \frac{1}{\sin(h_{MOON})}$ and $k = 0.2\ (\frac{magnitude}{airmass})$

Here h_{MOON} is the moon's altitude, and magnitude is the logarithmic unit of brightness such that 5 magnitudes corresponds to a factor of 100. This is equivalent to a difference of 1 magnitude corresponding to $100^{1/5}$ which is a factor of 2.512.

As light passes through the atmosphere it is scattered and absorbed, so astronomers have defined an airmass to measure the path length through the Earth's atmosphere. The airmass directly over head, at zenith, is defined to be one airmass. The number of airmasses increases as we increase the angle from zenith. So we needed to choose a reference airmass, $(airmass)_{ref}$, that would apply to the moonbow scenario that we were analyzing. A reference airmass of one was not chosen because if the Moon were directly overhead then the anti-moon would be directly under the viewer's feet and a moonbow would not be visible in Lower Yosemite Fall. Choosing the reference airmass to be along the horizon would be tricky due to the mountainous local horizon. So the airmass of 2.356 for an altitude of 25° was chosen as the reference airmass. Using these values in the equations for F_2 in our program would help us calculate the brightness due to atmospheric extinction.

Another important factor is the distance to the Moon, with the Moon appearing brighter at lunar perigee (near Earth) than at apogee (far from Earth). The effect of lunar distance on brightness of the Moon is as follows where R_{MOON} is the distance to the Moon in astronomical units:

$$Range_{MOON} = (1.495978707 * 10^8 km/AU)(R_{MOON})$$

$$F_3 = \left[\frac{(Range_{MOON})_{ref}}{Range_{MOON}}\right]^2 = \left[\frac{385001}{Range_{MOON}}\right]^2$$

Notice that $Range_{MOON}$ has units of kilometers rather than astronomical units. The mean distance to the Moon is 385001 km, so our reference $Range_{MOON}$ is chosen to be this value.

We also included the small variations in the Sun's distance, which changes the intensity of the sunlight reaching the Moon's surface in the following where R_{SUN} is the distance to the Sun in astronomical units:

$$F_4 = \left[\frac{(R_{SUN})_{ref}}{R_{SUN}}\right]^2 = \left[\frac{1.01\ AU}{R_{SUN}}\right]^2$$

The average distance to the Sun is 1 AU by definition of astronomical units. However, since Yosemite Falls only flows in the spring and early summer we only really need to consider the average distance of the Sun during these months. The mean distance of 1.01 AU to the Sun for 2005 occurred on May 11 so this is the value used in our program.

Each of these effects on the brightness of moonlight is calculated by our program and then multiplied to get a value expressing the relative brightness:

$$F_{TOTAL} = F_1 * F_2 * F_3 * F_4$$

The values for this range from a number greater than one to numbers much less. Our computer program requires that the moonlight be brighter than a cutoff value corresponding to a Moon at an altitude of 25 degrees, at its mean distance, and with an illumination fraction of 95%. The exact value for our cut of brightness is F_{TOTAL} = 0.53769.

Moonlight not Blocked by Mountains or Cliffs

Yosemite National Park is known for landmarks like Half Dome, Mount Starr King, Glacier Point, Sentinel Dome, and Sentinel Rock. However, the Moon must have risen above the local horizon formed by these nearby mountains, domes, and cliffs, so that moonlight can strike the spray at the base of the Lower Yosemite Fall. It would be incorrect to predict a moonbow for a certain date and time and then discover that the Moon was hidden behind a mountain or below the south rim of the valley. For any given date, we can determine the Moon's path in altitude and azimuth using data files calculated by the Jet Propulsion Lab Horizons software. To determine the exact profile of the local horizon, we needed to visit Yosemite and take photographs from the base of the fall where the mist is the thickest.

Correct Rainbow Geometry

The Lower Yosemite Fall viewing area is a paved terrace at the west end of a wooden bridge over Yosemite Creek. For an observer at this spot, a moonbow will only appear when the angle between the anti-lunar point and the direction toward the base of Lower Yosemite Fall is near 42 degrees, the rainbow angle. This concept is very well illustrated by Figure 2.

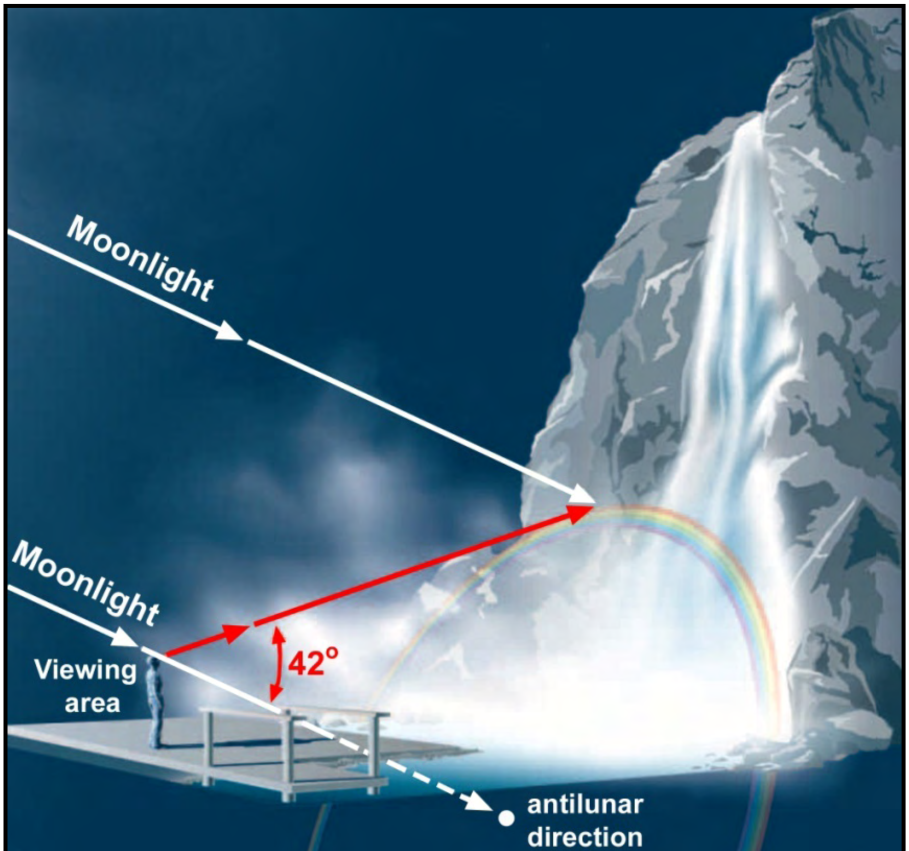


Figure 2: Diagram of basic moonbow geometry applied to Lower Yosemite Fall.

Sunlight is reflected from the Moon in all directions, but we can use the approximation that if two different locations are close in comparison to the distance from each of these locations to the Moon then the moonlight hitting these two points will be traveling parallel to each other. We can apply this approximation to our situation because if two individuals, one on the viewing area and the other in the mist where a moonbow is visible, were pointing at the center of the Moon their arms would be nearly parallel, as seen in Figure 2.

We needed to determine the region in the waterfall where a moonbow could occur then find the corresponding region in the sky that the Moon would need to pass through to form a moonbow in the waterfall. This would require understanding the topography to determine the relative positions of the viewing area and the fall. In order to get the measurements of the topography necessary to complete our computer program, we needed to visit Yosemite Falls.

Prior to visiting the park, we were able to derive a general equation that would allow us to determine if a moonbow were possible given the position of the Moon in the sky. This equation is used in our computer program to determine the precise time of the moonbow's occurrence. Figure 3 is the fundamental starting place for the entire derivation.

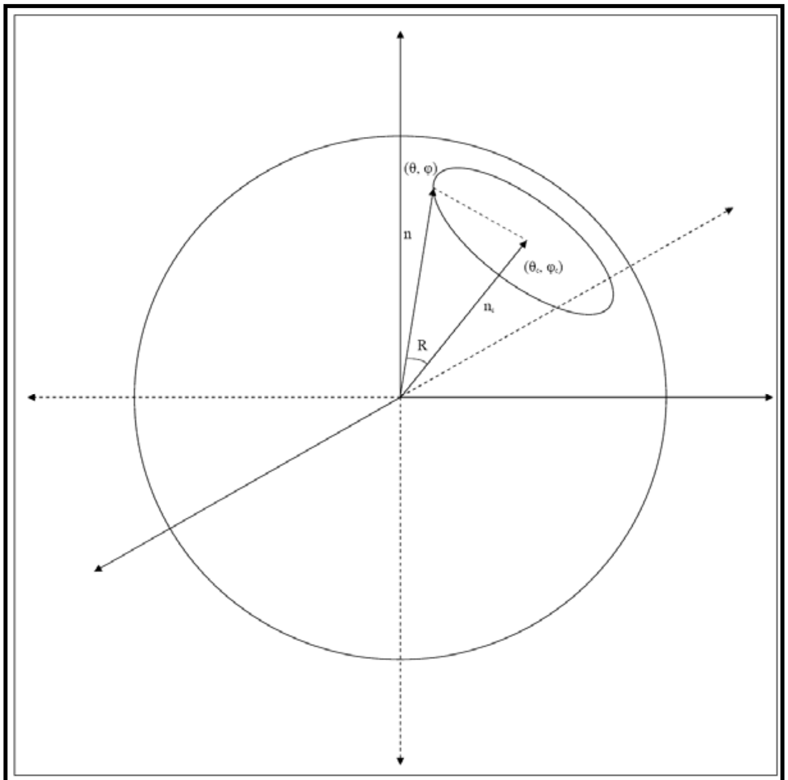


Figure 3: Sketch of a circle projected onto a sphere, in our case this helps us to determine the general equation for a moonbow.

The equation of a circle with angular radius R is

$$\boldsymbol{n} \cdot \boldsymbol{n_c} = |\boldsymbol{n}||\boldsymbol{n_c}| \cos R$$

If we are certain to use only the unit vectors in the direction of n and n_c, then

$$\cos R = n_x(n_c)_x + n_y(n_c)_y + n_z(n_c)_z$$

The components of an arbitrary unit vector are

$$x = \sin\theta \cos\varphi$$

$$y = \sin\theta \sin\varphi$$

$$z = \cos\theta$$

Thus

$$\cos R = (\sin\theta \cos\varphi)(\sin\theta_c \cos\varphi_c) + (\sin\theta \sin\varphi)(\sin\theta_c \sin\varphi_c) + \cos\theta \cos\theta_c$$

$$\cos R = (\sin\theta \sin\theta_c)(\cos\varphi \cos\varphi_c + \sin\varphi \sin\varphi_c) + \cos\theta \cos\theta_c$$

$$\cos R = (\sin\theta \sin\theta_c) \cos(\varphi - \varphi_c) + \cos\theta \cos\theta_c$$

Therefore the general equation for the circle with angular radius R is

$$\cos R = (\sin\theta \sin\theta_c) \cos(\varphi - \varphi_c) + \cos\theta \cos\theta_c$$

We apply this general equation for the circle with angular radius R to our situation where the circle is centered on the anti-moon and in order to form a moonbow R must be 42.3 degrees. So the equation becomes

$$\cos R = \sin h \sin h_{AM} \cos(A - A_{AM}) + \cos h \cos h_{AM}$$

where h_{AM} is the altitude of the anti-moon and A_{AM} is the azimuth of the anti-moon. Since the input parameters of the program are azimuth and altitude of the Moon, we must realize that $A_{AM} = A_M + 180°$ and $h_{AM} = -h_M$.

For fun and to help determine the accuracy of our predictions we decided we also wanted to be able to predict the position of the moonbow in the fall relative to the densest part of the mist and the slant of the bow.

Determining the angular separation, D, between the anti-moon and the waterfall was simply a matter of realizing that the circle should pass through the waterfall. So

$$\cos R = \sin h_{WF} \sin h_{AM} \cos(A_{WF} - A_{AM}) + \cos h_{WF} \cos h_{AM}$$

where h_{WF} is the altitude of the waterfall relative to the observer and A_{WF} is the azimuth of the waterfall. Because the mist is not a point but a large region, we extend the moonbow region to be an area extending to roughly 8 degrees above and 5 degrees below the densest spray near the base of the fall.

Calculating the slope of the moonbow at the point nearest the center of the mist turned out to be a far more daunting task. Meeus's *Astronomical Algorithms* p.117 gives us the equation for a great circle

$$\tan\delta_A \sin(\alpha_B - \alpha) + \tan\delta_B \sin(\alpha - \alpha_A) + \tan\delta \sin(\alpha_B - \alpha_A) = 0$$

In this equation, α_A is the azimuthal position of A, δ_A is the altitude of A, α_B is the azimuth of B, and δ_B is the altitude of B.

Take the differential of the equation above, $f(\alpha,\delta) = 0$:

$$\frac{\partial f}{\partial \alpha} d\alpha + \frac{\partial f}{\partial \delta} d\delta = 0$$

$$\tan\delta_A \cos(\alpha_B - \alpha)(-1)d\alpha + \tan\delta_B \cos(\alpha - \alpha_A)(+1)d\alpha + (\sec\delta)^2 \sin(\alpha_A - \alpha_B) = 0$$

$$d\alpha[\tan\delta_B \cos(\alpha - \alpha_A) - \tan\delta_B \cos(\alpha - \alpha_B)] = (\sec\delta)^2 \sin(\alpha_B - \alpha_A)\, d\delta$$

The following equation is valid anywhere on the great circle:

$$\frac{d\alpha}{d\delta} = \frac{(\sec\delta)^2 \sin(\alpha_B - \alpha_A)}{\tan\delta_B \cos(\alpha - \alpha_A) - \tan\delta_A \cos(\alpha - \alpha_B)}$$

However, we want to evaluate this equation at the point A where $\alpha = \alpha_A$ and $\delta = \delta_A$.

$$\frac{d\alpha}{d\delta}|_A = \frac{(\sec\delta_A)^2 \sin(\alpha_B - \alpha_A)}{\tan\delta_B \cos(\alpha_A - \alpha_A) - \tan\delta_A \cos(\alpha_A - \alpha_B)}$$

$$\frac{d\alpha}{d\delta}|_A = \frac{(\sec\delta_A)^2 \sin(\alpha_B - \alpha_A)}{\tan\delta_B - \tan\delta_A \cos(\alpha_B - \alpha_A)}$$

$$\frac{d\alpha}{d\delta}|_A = \left[\frac{\sin(\alpha_B - \alpha_A)}{(\cos\delta_A)^2 \frac{\sin\delta_B}{\cos\delta_B} - (\cos\delta_A)^2 \frac{\sin\delta_B}{\cos\delta_B}\cos(\alpha_B - \alpha_A)}\right]\left(\frac{\cos\delta_B}{\cos\delta_B}\right)$$

$$\frac{d\alpha}{d\delta}|_A = \frac{\cos\delta_B \sin(\alpha_B - \alpha_A)}{(\cos\delta_A)^2 \sin\delta_B - \cos\delta_A \cos\delta_B \sin\delta_B \cos(\alpha_B - \alpha_A)}$$

Finally

$$\frac{d\alpha}{d\delta}|_A = \frac{\sin(\alpha_B - \alpha_A)}{(\cos\delta_A)^2[\tan\delta_B - \tan\delta_A \cos(\alpha_B - \alpha_A)]}$$

Since

$$Slope = \tan\Psi = \frac{\cos\delta\, d\alpha}{d\delta} = \cos\delta \frac{d\alpha}{d\delta}$$

$$\tan\Psi|_A = \frac{\sin(\alpha_B - \alpha_A)}{(\cos\delta_A)[\tan\delta_B - \tan\delta_A \cos(\alpha_B - \alpha_A)]}$$

We can correlate this general equation for a random point on the great circle to a moonbow through Lower Yosemite Fall by letting the point A be a point in the center of the mist at the base of the waterfall and the point B be the anti-moon. Therefore the slope of the moonbow is

$$\tan\alpha = \frac{\sin(A_{WF} - A_{AM})}{\cos h_{WF}\,[\tan h_{AM} - \tan h_{WF}\cos(A_{WF} - A_{AM})]}$$

So there are three very distinct cases for the appearance of the moonbow through the center of the mist: $\alpha > 0$, $\alpha = 0$, and $\alpha < 0$. For $\alpha > 0$, the slope of the moonbow can be described in much the same way as a positive sloping line, rising from lower left to upper right. When $\alpha = 0$ the moonbow is perfectly horizontal through the mist. Finally when $\alpha < 0$ then the slope of the mist is like a negatively sloping line, falling from upper left to lower right.

Figure 4: Three photographs taken from the viewing area of moonbows in Lower Yosemite Fall. Each photograph exhibits a different possible slope of the moonbow.

However, now we needed to understand the topography, to determine the relative position of the viewing area and the fall, which provided another reason to travel to Yosemite.

VISITING YOSEMITE

Fortunately, Dr. Olson's group was finishing up a previous project in Yosemite National Park. In a previous Sky & Telescope article, the group had predicted that on September 15, 2005, the Moon's position would recreate the famous Ansel Adams photograph "Autumn Moon" (S&T: October 2005, page 40). The moonrise event at Glacier Point was a great success, with hundreds of photographers in attendance (S&T: January 2006, page 93), but most of the time in the park was spent near Lower Yosemite Fall.

In September, the water running over the falls is little more than a trickle. This would have been bad news for those hoping to witness the thunderous Yosemite Falls, but for our research group this was good news. With the falls in this state we could stand at the base of the falls which is impossible during the spring runoff season.

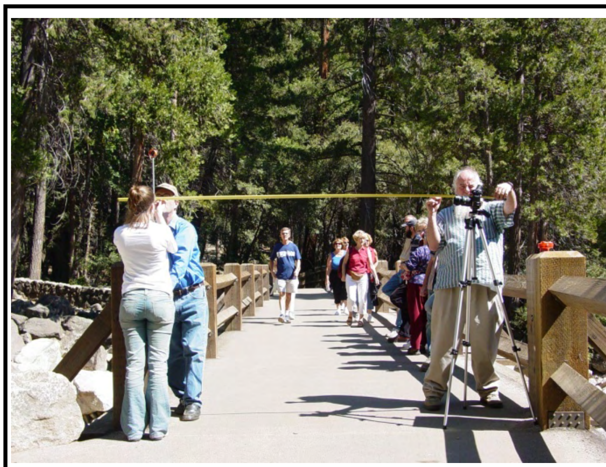


Figure 5: Ashley Ralph, Roger Sinnott, and Russell Doescher making measurements on the bridge near the viewing area.

Figure 6: In this photograph, the stars make it possible to determine the precise location of formations on the local horizon.

During the day we surveyed the falls with rulers, plumb bobs, and a laser level. At night we took photographs of the nearby mountains and cliffs silhouetted against brilliant star fields. The known altitudes and azimuths of the stars would be used to accurately trace out the profile of the local horizon and determine the relative location of the waterfall from the viewing area.

Location of Lower Yosemite Fall: Distance

Prior to our trip, we used information from a variety of online sources to do some preliminary calculations. One of these websites was summitpost.org, a well respected resource for climbing, mountaineering, hiking, and other outdoor activities. This web site had informed us that Lower Yosemite Fall would be about 100 yards from the bridge. However, we used our measurements of the width between two posts on the bridge and the angular scale of the bridge determined from a photograph of the bridge taken from the base of the falls to determine the actual distance from the base of the falls to the viewing area. The final result of our calculations and extensive use of the law of sines is that the distance between the base of the falls and the viewing area is 537 feet or 179 yards.

Location of Lower Yosemite Fall: Azimuth and Altitude

At night we took photographs of Lower Yosemite Fall from the viewing area in order to determine two important angles, azimuth and altitude. The photographs taken at night with time-exposure photography showed star trails through the sky above Yosemite Falls. Since we know the precise times when the photographs were taken, we used star charts to identify the stars in the sky then the computer program Voyager to determine the azimuth and altitude of each of the stars in the sky at that time. Using trigonometry and algebra to extrapolate these values we found that the azimuth from the viewing area to the densest part of the mist in Lower Yosemite Fall was 325 degrees. Because Yosemite Falls are so tall, we decided that it would be best to use these stars to determine the azimuth, but the extrapolation to find the value for altitude would make the results very inaccurate.

Figure 7: Photograph of stars over the top of Lower Yosemite Fall used to determine location of the densest part of the mist.

In order to determine the altitude of the densest part of the mist in the falls, we used the results of surveying the falls during the daylight. The photographs of a ruler held vertical (using a plumb bob and laser level) on the bridge in front of the falls were used to determine the altitude of the densest part of the mist to be 12 degrees.

In these ways we determined a person at the center of the viewing terrace would observe the densest part of the spray near the base of Lower Yosemite Fall by facing toward azimuth 325 degrees (that is, 35 degrees west of north) and looking somewhat upward, toward an altitude of +12 degrees.

Figure 8: Roger Sinnott, myself, and Ashley Ralph use the measuring tape and laser level to create an altitude scale.

Local Horizon

After visiting the park we returned with photographs of the local horizon taken both during the day and at night. The photographs taken at night with time-exposure photography showed the local horizon as well as star trails through the sky above these distinctive landmarks. Since we know the precise times when the photographs were taken, we needed to identify the stars in the sky then use Voyager to determine the azimuth and altitude of each of the stars in the sky at that time. From these values we would be able to determine precisely where the local horizon was located.

After determining the local horizon for the computer program, we decided it would be helpful to have a diagram of the local horizon with the Moon's lines of declination and the successful moonbow region drawn on it in order to help us to interpret our results. We used graph paper to make sure that our local horizon would be drawn as precisely as possible. We also added in the lines of declination on which the Moon rises in the sky and then finally we added the successful moonbow region. We used the equations derived when determining the correct rainbow geometry, then expanding the region to 8 degrees above and 5 degrees below the densest part of the mist. We used the successful values for the anti-moon location in order to determine where in the sky the Moon could be to produce the moonbow. The result was Figure 9.

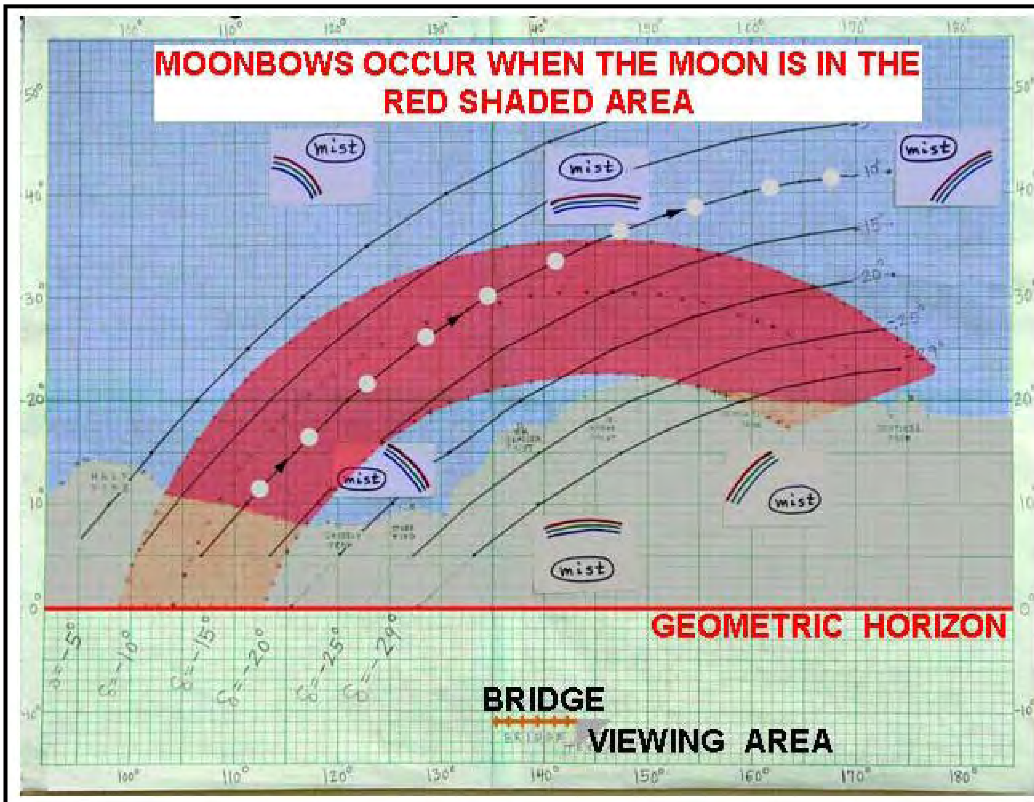


Figure 9: This is the chart we came up with to help us to understand where in the sky the Moon should be in order to create a moonbow in Lower Yosemite Fall for viewers at the viewing area.

This chart was helpful when checking the output of the computer program against previously photographed moonbows. Using the chart we were able to conceptually understand how the Moon was moving through the sky and as a result how the moonbow was behaving in the waterfall.

FINISHING THE COMPUTER PROGRAM

Following our trip to Yosemite National Park, we had the values of azimuth and altitude for the location of Lower Yosemite Fall and the local horizon. Now we could use these values and the equations derived to model the brightness of the moonlight and correct rainbow geometry in our MOONBOWS program. Writing the program in BASIC turned out to be simple once the equations were derived. The code for the program, and sample input and output files can be found in Appendix C. The input file is created using JPL Horizons Ephemeris to generate the information on position of the Sun and Moon in the sky, the distance of the Sun and Moon from earth, declination of the Moon and percent illumination of the Moon for every minute of a specified range of time. This is used by our MOONBOWS program to produce an output file which contains the time, percent illumination of the Moon, declination of the Moon, location of the Sun and Moon, the success ("***") or failure("   ") of a moonbow, the location of the moonbow in the mist, the slope of the moonbow in the mist, and the brightness of the moonlight. With this program, we are able to determine the days in spring runoff season near full Moon that we would like to check for the occurrence of a moonbow. Then we use our chart in order to consider which days to post in our table of predictions.

CASE OF THE MISSING MOONBOW: SOLVED

An example for a specific date and time will help explain the process. Let's return to the case of the mysteriously absent moonbow on the evening June 22, 2005, that left approximately 50 photographers disappointed. We took the information generated by JPL Horizons Ephemeris and created an input file for our MOONBOW program. The result of the program was not a missing moonbow, but rather a moonbow arriving in the early hours of the next morning.

On June 23, 2005, at 1:30 a.m. PDT a bright nearly-full Moon (98% illuminated) had risen above the south rim of Yosemite Valley and stood in the sky at azimuth 169 degrees and altitude 23 degrees. Equations based on spherical trigonometry show that the anti-lunar point was then separated from the densest spray at the base of Lower Yosemite Fall by an angle of exactly 42 degrees – perfect conditions for a moonbow.

Recognizing that the mist occupies a region, extending from approximately 8 degrees above to about 5 degrees below the densest spray near the base of the fall, our program finds that a moonbow would have been visible during the entire period from 12:45 a.m. to 2:00 a.m. PDT on June 23, 2005. As the Moon rose higher into the sky and moved westward, the bow first appeared near the top of the spray and then slowly drifted downward and eastward.

We now had the explanation for the disappointing experience of the Calphoto group on the evening of June 22, 2005. The Moon did finally clear the local horizon, and a bright moonbow did eventually appear, but not until the early hours of the next morning. We realized that our calculations of dates and precise times could save people from long and disappointing waits in a location that can be cold and wet.

MOONBOW PREDICTIONS

During the snowmelt runoff season of 2006, we tested our program by circulating predicted dates and times to the Calphoto discussion list and to other interested photographers. The photographic results from 2006 verified the accuracy of the program. Predictions were posted for 2007, 2008, and 2009 on Dr. Olson's website, http://uweb.txstate.edu/~do01/. These predictions for all four years can also be found in Appendix B.

Our computer program typically predicts moonbows on four or five nights near each full Moon during the snowmelt runoff period. This is perhaps slightly conservative but is in general agreement with the conclusions of the sharp-eyed John Muir, who judged:

> "…magnificent lunar bows may be found for half a dozen nights in the months of April, May, June, and sometimes July."
>
> (John Muir, "Yosemite in Spring", New York *Tribune*, May 7, 1872)

Thus far our program has successfully predicted Moonbows for 2006 and 2007 snowmelt runoff seasons. In addition to Dr. Olson's website, these results have been posted in a variety of publications such as *Sky & Telescope*, *Chinese National Astronomy*, the *Houston Chronicle*, *Los Angeles Times*, and *Weekly Reader*. Some of these articles can be found in Appendix A.

CONCLUSIONS

We have written a computer program that can accurately predict when moonbows will be visible in Lower Yosemite Fall from the viewing area. This program relies on information gathered from JPL Horizons Ephemeris and measurements collected from the park by Dr. Olson's research group.

If you don't have plans to visit Yosemite National Park to see this lunar phenomenon, don't worry because in addition to bows in rain showers and waterfalls, anyone can make a moonbow with a hose in the backyard. With a bright Moon high in the sky, direct a fine mist toward a spot 42 degrees away from the shadow of your head. The bow is much easier to see against a dark background, like a dark bush or a dark wall. Once seen, the ethereal silver-white of the moonbow is not easily forgotten.

Appendix A

Our three moonbow articles and articles written about our work were published in a variety of magazines, newspapers, and webpages. The following are a few publications of our work:

Moonbows *over* Yosemite

By Donald W. Olson, Russell L. Doescher,
and the Mitte Honors Students

The rainbow occurs by day, and it was formerly thought that it never appeared by night as a moon rainbow. This opinion was due to the rarity of the phenomenon: it was not observed, for though it does happen, it does so rarely. . . . The colors are not easy to see in the dark. . . . The moon rainbow appears white.

— Aristotle, *Meteorologica,* about 340 BC

More than mountain air and daytime scenery beckon visitors to Yosemite National Park each spring — many go for a chilly, damp, nighttime vigil.

Few sights evoke such spontaneous delight and wonder as a late-afternoon rainbow bursting into view in the eastern sky after a spring downpour. Even before it appears, you sense that it might, and you keep a lookout. Maybe you once fancied finding a pot of gold where the colorful arc ends.

Yet how many of us have seen a rainbow at night? While this is a fairly rare event, nature lovers as far back as Aristotle knew it was possible for a bright Moon, like the Sun, to produce a rainbow.

When rays of light from the Sun (or Moon) shine on spherical drops of water in a rain shower, a combination of refraction, internal reflection, and dispersion can produce a rainbow display. The primary bow forms a circular arc with a radius of 42°, and under good conditions a much fainter secondary rainbow can appear with a radius of 51° and with the sequence of colors reversed.

By day the center of the rainbow is the *antisolar point,* the point exactly opposite the Sun and therefore marked by the shadow of your head. It is located as far below the horizon as the Sun is above the opposite horizon. At night the geometry is the same except that the antilunar point (opposite the Moon) is the center for this display — known as a lunar rainbow, moon rainbow, or moonbow.

Time-exposure photographs show that the full palette of col-

Kim Steinbacher set up her tripod at the viewing area near the base of Lower Yosemite Fall to capture this double moonbow about 11 p.m. PDT on May 22, 2005. With mist and spray blowing down from the fall, she struggled to keep the camera and lens dry during the long exposure.

BRENT GILSTRAP

A reflected moonbow appears in this unusual scene captured by Brent Gilstrap near 1:20 a.m. PDT on May 15, 2006, from the edge of the parking lot next to Sentinel Bridge (some 900 yards farther back than the usual viewing area). The image is a four-frame vertical panorama made from three 30-second exposures and (at bottom) a 60-second exposure. The reflection is from Cook's Meadow, which was flooded by an unusually large spring runoff. Yosemite National Park had received about twice the normal snowfall during the preceding winter.

ors is present in lunar rainbows. The human eye loses most of its color sensitivity in dim light, and visual observers usually describe moonbows as gray, white, or silver. But under ideal conditions — clear air, abundant water drops, and bright moonlight from a full or nearly full Moon — some people have reported seeing the colors in lunar rainbows.

Mark Twain and Moonbows

In his 1872 travel narrative *Roughing It* (chapter 71), Mark Twain records such an observation that he made in 1866 during a trip to Hawaii:

> *Why did not Captain Cook have taste enough to call his great discovery the Rainbow Islands? These charming spectacles are present to you at every turn; they are common in all the islands; they are visible every day, and frequently at night also — not the silvery bow we see once in an age in the States, by moonlight, but barred with all bright and beautiful colors, like the children of the sun and rain. I saw one of them a few nights ago.*

The celebrated author was returning to America from a European tour in 1879 when he again experienced near-ideal conditions. He described what he saw in a notebook entry for August 31, 1879:

> *At sea in the "Gallia" . . . about 9 PM brilliant moon, a calm sea, & a magnificent lunar rainbow — a complete arch, the colors part of the time as brilliant as if it were noonday — some said not* quite *as brilliant, softened with a degree of vagueness, but to me it was not different from a daylight rainbow.*

Twain considered himself very fortunate to have seen this wonder twice in his life.

Ben Franklin at Sea

Another account of a lunar rainbow at sea comes from the young Benjamin Franklin, on a return voyage from London to Philadelphia in 1726. His journal entry for August 30th (Julian calendar), equivalent to September 10th (Gregorian calendar), reads:

> *Contrary wind still. This evening the moon being near full, as she rose after eight o'clock, there appeared a rainbow in a western cloud to windward of us. The first time I ever saw a rainbow in the night caused by the moon.*

Astronomers will find much of interest in Franklin's journal for this trip, including his observations of a partial solar eclipse and then, two weeks later, a partial lunar eclipse.

Moonbows and Waterfalls

Instead of waiting for a rain shower on a moonlit night, observers can find moonbows more reliably in the spray near waterfalls. At Victoria Falls, on the border between Zambia and Zimbabwe, tour companies offer "lunar rainbow tours." Moonbow observing is also a popular activity at Cumberland Falls in Kentucky, and early postcards show a hotel named the Moonbow Inn adjacent to the falls. Lunar bows were a great tourist attraction at Niagara Falls in the years before the installation of artificial night lighting, and two topographic features there (Luna Island and Luna Falls) took their name from the phenomenon.

Muir and Yosemite Moonbows

John Muir, the naturalist largely responsible for the creation of Yosemite National Park, eloquently described moonbows in waterfalls:

> *Lunar rainbows or spray-bows also abound in the glorious affluence of dashing, rejoicing, hurrahing, enthusiastic spring floods, their colors as distinct as those of the sun and regularly and obviously banded, though less vivid. Fine specimens may be found any night at the foot of the Upper Yosemite Fall, glowing gloriously amid the gloomy shadows and thundering waters, whenever there is plenty of moonlight and spray. Even the secondary bow is at times distinctly visible.*

In his 1912 book *The Yosemite,* Muir urged visitors

S&T: ROGER W. SINNOTT

RUSSELL DOESCHER

S&T: ROGER W. SINNOTT

Left: In September 2005, the authors use rulers, plumb bobs, and a laser level to make a topographic survey at the viewing area near the base of Lower Yosemite Fall. Left to right are Kellie Beicker, Russell Doescher, and Don Olson. *Center:* Joined by *Sky & Telescope* senior editor Roger Sinnott (left), the group determines the direction of the geometric horizon and the distance to the base of the fall, which was nearly dry at this season. Ashley Ralph is at right. *Right:* Olson and Doescher plan the sky photographs they would need to take from the base of the fall at night.

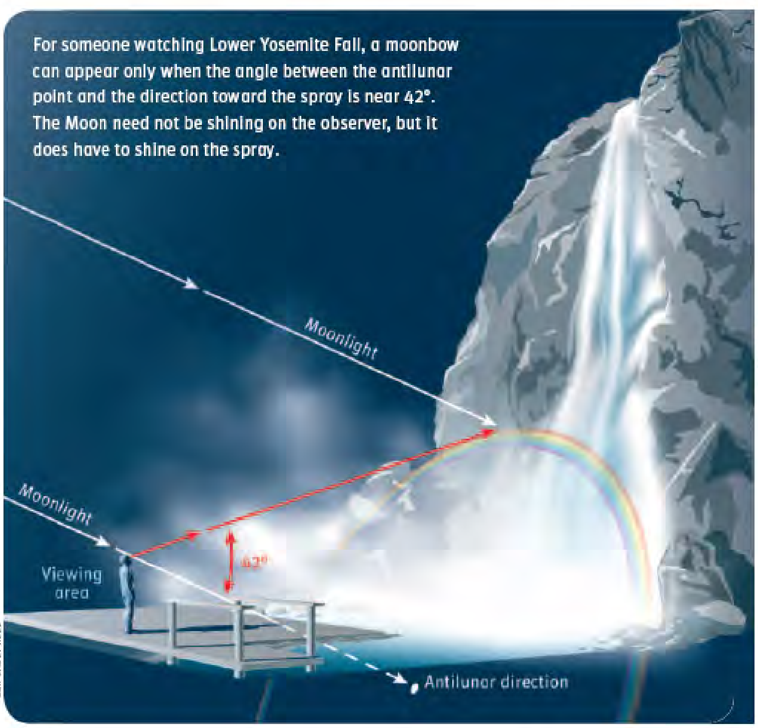
to explore Yosemite Valley at night and to look for the moonbow:

> *This grand arc of color, glowing in mild, shapely beauty in so weird and huge a chamber of night shadows, and amid the rush and roar and tumultuous dashing of this thunder-voiced fall, is one of the most impressive and most cheering of all the blessed mountain evangels.*

Standing alone in the night near the north rim of the valley, Muir delighted in the magical sights that have drawn pilgrims to this place on moonlit nights for more than a century:

> *The moonbeams were pouring through. . . . I saw a well-defined spray-bow, beautifully distinct in colors . . . while pure white foam-waves beneath the beautiful bow were constantly springing up out of the dark into the moonlight like dancing ghosts.*

Four decades earlier, in April 1871, Muir had written in a letter to Mrs. Jeanne S. Carr, "Silver from the moon illumines this glorious creation which we term 'falls,' and has laid a magnificent double prismatic bow at its base. The tissue of the fall is delicately filmed on the outside like the substance of spent clouds, and the stars shine dimly through it."



For someone watching Lower Yosemite Fall, a moonbow can appear only when the angle between the antilunar point and the direction toward the spray is near 42°. The Moon need not be shining on the observer, but it does have to shine on the spray.

S&T: CASEY REED

SIMONE RIVERS

Above: The arrow points to the Lower Yosemite Fall viewing area, a paved terrace at the west end of the wooden bridge over Yosemite Creek. The viewing area, a popular spot for moonbow observing and photography, is 180 yards from the base of the fall.

Inspired by Muir's dramatic accounts, we decided to write a computer program to predict dates and precise times when moonbows would appear in the Yosemite waterfalls.

Missing Moonbow in 2005?

While searching for moonbow-related messages in the archive of Calphoto, a Yahoo Groups discussion forum about nature photography in California, we ran across an incident that made us realize how useful our program's predictions might be.

On the evening of June 22, 2005, the Moon was just slightly past full with 98% of its disk illuminated. Accordingly, about 50 photographers gathered under a clear sky at the viewing area near the base of Lower Yosemite Fall to await the moonbow. As the evening wore on, the temperature dropped toward freezing, and mist blowing down from the waterfall made it impossible to stay dry. By about midnight the gathering broke up in disappointment.

On the discussion list the next day, group members wondered why the moonbow had failed to appear, even with "all obvious conditions in place." One message ended with the words: "What has changed to eliminate this other unique feature of Yosemite?"

Computing Moonbow Visibility

We realized that six conditions must be simultaneously met for a moonbow to be readily visible at Lower Yosemite Fall. The first two conditions are weather dependent, but the last four are astronomical and can be modeled by a computer program:

- **CLEAR SKY AROUND THE MOON.**
- **ABUNDANT MIST AND SPRAY AT THE BASE OF THE FALL.** The best moonbows at Yosemite occur during the snowmelt runoff season of April, May, June, and sometimes early July.
- **DARK SKY.** Our program requires that the Sun be more than 9° below the geometric horizon.
- **BRIGHT MOONLIGHT.** The Moon's brightness depends on its phase, distance from Earth, and altitude. Our program requires that the moonlight be brighter than a cutoff value corresponding to a Moon at an altitude of 25°, at its mean distance, and with an illuminated fraction of 95%.
- **MOONLIGHT NOT BLOCKED BY MOUNTAINS OR CLIFFS.** For moonlight to strike the spray at the base of Lower Yosemite Fall, the Moon must have risen above the nearby mountains, domes, and cliffs. To determine the profile of the local horizon, we needed to visit Yosemite and take photographs from the base of the fall.
- **CORRECT RAINBOW GEOMETRY.** The Lower Yosemite Fall viewing area is a paved terrace at the west end of a wooden bridge over Yosemite Creek. For an observer at this spot, a moonbow will appear only when the angle between the antilunar point and the direction toward the base of the fall is near the rainbow angle of 42°. Understanding this topography provided another reason to travel to Yosemite.

WWW.CALVINBRADSHAW.COM

A spectacular moonbow forms in the mist from Victoria Falls as the stars of Orion set behind it. Calvin Bradshaw was visiting Africa from Brisbane, Australia.

Trip to Yosemite

Fortunately, our Texas State group already had a Yosemite trip scheduled! In a previous *Sky & Telescope* article (October 2005, page 40) we predicted that on September 15, 2005, the Moon's position would recreate the scene in a famous Ansel Adams photograph from Glacier Point. That moonrise event was a great success, with hundreds of photographers in attendance (*S&T:* January 2006, page 93), but we actually spent most of our time in the park near Lower Yosemite Fall.

The flow of water was reduced to a trickle in September, which worked to our advantage. We could stand right at the base of the fall, something impossible in the thundering torrents of the spring runoff season. We took photographs at night with the nearby mountains and cliffs silhouetted against brilliant star fields. The known altitudes and azimuths of the stars allowed us to accurately map the local horizon.

By day we did conventional surveying with rulers, plumb bobs, and a laser level. Websites had informed us that Lower Yosemite Fall would be about 100 yards from the viewing area, but our survey found that this distance is actually 180 yards (165 meters). We also determined values for two important angles. A person at the center of the viewing terrace would see the densest part of the spray by facing toward azimuth 325° (that is, 35° west of north) and looking somewhat upward at an altitude of 12°. We now had all the information we needed.

Case of the Missing Moonbow: Solved!

An example will help explain the geometry. On June 23, 2005, at 1:30 a.m. Pacific Daylight Time, a bright, nearly full Moon had risen above the south rim of Yosemite Valley and stood in the sky at azimuth 169° and altitude 23°. Trigonometry shows that the antilunar point (azimuth 169° + 180° = 349°, altitude −23°) was then separated from the densest spray at the base of Lower Yosemite Fall by an angle of exactly 42°. Conditions were perfect for a moonbow.

Given that the mist occupies a rather large region, extending from roughly 8° above to 5° below the densest spray near the base of the fall, our program finds that a moonbow would have been visible from 12:45 to 2:00 a.m.

Rob Ratkowski captured a moonbow, stars, and three planets in this spectacular image looking west near Kahului, Maui, after sunset on May 4, 2004. Behind the photographer a full Moon was rising into the eastern sky. In the west the brightest object was Venus, inside the moonbow and close to Beta (β) Tauri. Above and left of Venus are Mars (inside the bow) and Saturn (outside the bow, among stars of Gemini).

PDT on June 23, 2005. As the Moon rose higher and moved westward, the bow first appeared near the top of the spray and slowly drifted downward and eastward.

We now had an explanation for the disappointing experience of the Calphoto group on the evening of June 22, 2005. The Moon *did* finally clear the local horizon, and a bright moonbow *did* eventually appear, but not until the early hours of the next morning! We realized that our calculations of dates and precise times could save people from long and disappointing waits in the cold and wet.

2006 and 2007

During the snowmelt runoff season of 2006, we tested our program by circulating predicted dates and times to the Calphoto list and to other interested photographers. The photographic results verified the program's accuracy.

The table here gives our moonbow predictions for 2007. Our Texas State website, http://uweb.txstate.edu/~do01, contains more detailed descriptions of the position of the Moon and appearance of the moonbows in 2007, along with links to moonbow photographs from 2006.

Our program typically predicts moonbows on four or five nights near each full Moon during the snowmelt runoff period. This is perhaps slightly conservative. But it's in general agreement with the conclusions of the sharp-eyed John Muir, who judged, "Magnificent lunar bows may be found for half a dozen nights in the months of April, May, June, and sometimes July" (*New York Tribune*, May 7, 1872).

Rain showers and waterfalls are not the only settings where this phenomenon takes place. Anyone can make a moonbow with a garden hose! With a bright Moon high in the sky, direct a fine mist toward a spot 42° away from the shadow of your head. The bow is much easier to see against a dark background, such as a dark bush or wall. Once seen, the ethereal silver-white of the moonbow is not easily forgotten. ✴

Moonbow Predictions for Lower Yosemite Fall

Evening Date in 2007	Pacific Daylight Time	Lunar Phase
April 29 (Sunday)	8:32 p.m. (Sun.) to 9:20 p.m. (Sun.)	96%
April 30 (Monday)	8:33 p.m. (Mon.) to 10:40 p.m. (Mon.)	99%
May 1 (Tuesday)	10:05 p.m. (Tues.) to 11:50 p.m. (Tues.)	100%
May 2 (Wednesday)	11:25 p.m. (Wed.) to 1:00 a.m. (Thurs.)	99%
May 3 (Thursday)	12:37 a.m. (Fri.) to 2:00 a.m. (Fri.)	96%
May 29 (Tuesday)	9:10 p.m. (Tues.) to 10:50 p.m. (Tues.)	97%
May 30 (Wednesday)	10:26 p.m. (Wed.) to 11:50 p.m. (Wed.)	99%
May 31 (Thursday)	11:33 p.m. (Thurs.) to 12:55 a.m. (Fri.)	100%
June 1 (Friday)	12:39 a.m. (Sat.) to 1:50 a.m. (Sat.)	98%
June 28 (Thursday)	10:35 p.m. (Thurs.) to 11:25 p.m. (Thurs.)	98%
June 29 (Friday)	11:30 p.m. (Fri.) to 12:20 a.m. (Sat.)	100%
June 30 (Saturday)	12:20 a.m. (Sun.) to 1:05 a.m. (Sun.)	99%
July 1 (Sunday)	12:55 a.m. (Mon.) to 1:45 a.m. (Mon.)	96%

All calculations are for the prime viewing area, the terrace at the west end of the wooden bridge near the base of Lower Yosemite Fall.

Don Olson *and* Russell Doescher *teach physics at Texas State University.* *They are grateful for support from the Mitte Honors Program, which made it possible for students Kellie N. Beicker, Ashley B. Ralph, and Hui-Yiing Chang to work on this project during the 2005–06 academic year. They also appreciate research assistance from Margaret Vaverek of Texas State's Alkek Library and from moonbow photographers Matt Asat, Mark Bright, Carl Bruce, Brent Gilstrap, Grant Johnson, Jia Liu, Robert Stavers, Kim Steinbacher, and Keith Walklet.*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目录 CONTENTS

附赠：《中国国家天文》从2007年第1期开始，每期为您呈送美国《Sky&Telescope》杂志独家提供的精美星图，以有助于您认知近期的灿烂星空。

SKY & TELESCOPE 授权同步刊登

约塞米蒂上空的

月虹

每年春天，除了山风和日光，还有更多的理由吸引人们前往美国约塞米蒂（Yosemite）国家公园。很多人到那里去，就是为了领略沐浴在凉爽和湿润的微风中守夜之趣。

文/Donald W.Olson、Russell L. Doescher 及获得“Mitte Honors”奖学金计划的学生们　编译/林清

在人们的常识中，彩虹一般发生在白天。在夜间因月光而发生彩虹好像是不太可能的事。这种观念的形成，是因为月光彩虹实在是太罕见了，人们几乎从来无缘相遇。……因为它的暗弱，其色彩难以显现出来，……月光彩虹看起来是白色的。

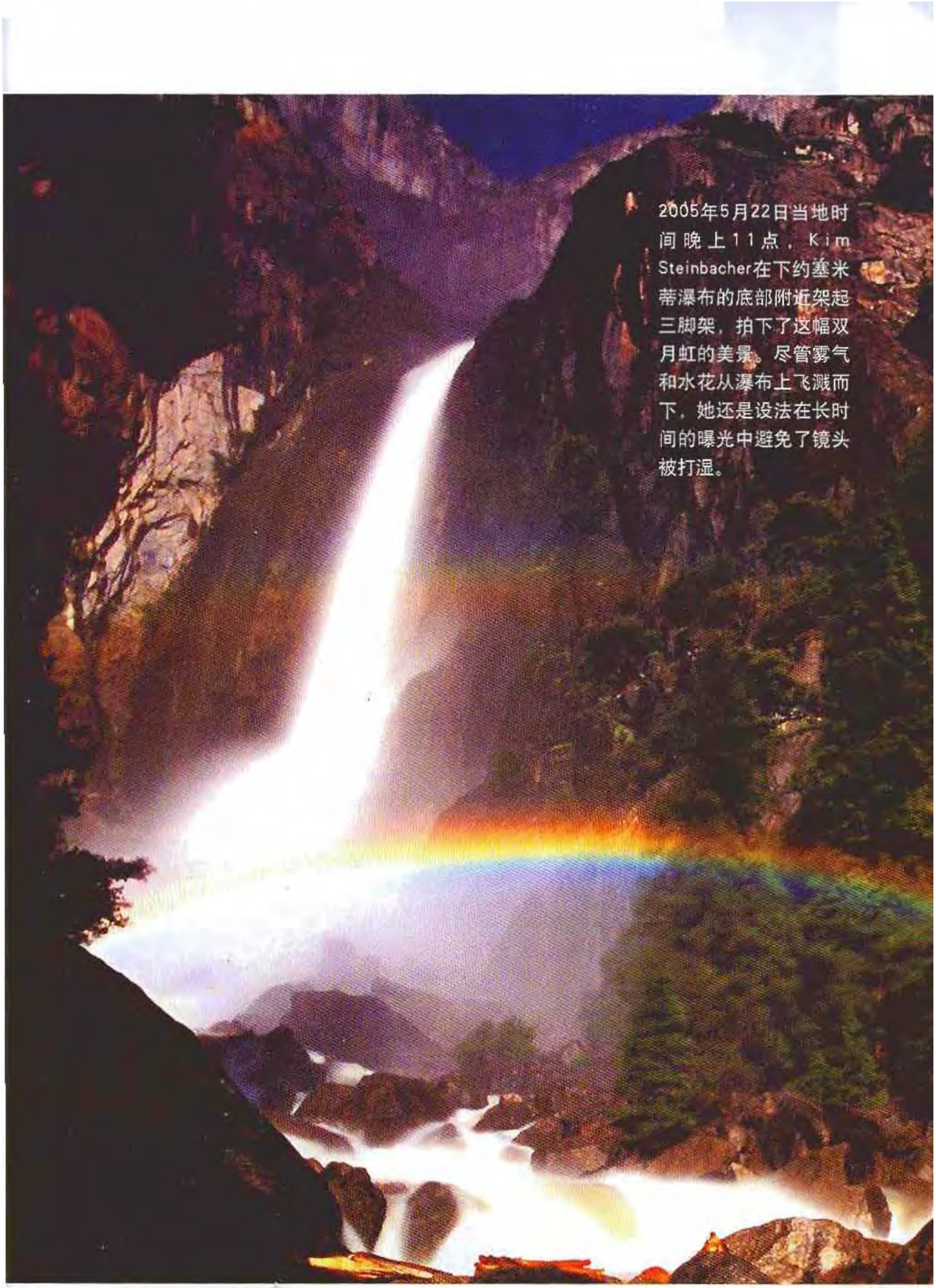
——亚里斯多德《气象学》（约公元前340年）

春天，午后一场暴雨扫过，东方天空中迸现一道绚丽壮观的彩虹，大概很少有哪种景象比它更容易引起人们的激动和赞叹了。在它出现之前，你就可能预感并守候它的出现。有时，你可能还会为在彩弧结束的地方发现一抹金色而欢呼。

但是，我们中有多少人在夜间看到过彩虹呢？这个现象相当的罕见，但是，早至亚里斯多德的时代，这位有名的大自然爱好者已经知道，明亮的月亮和太阳一样，也可能产生彩虹。

雨后，如果来自太阳（或月亮）的光线投射在雨中的球状水滴上，光的折射、反射和散射等因素综合作用，就会产生彩虹。一级彩虹会形成一个张角42度的弧形。条件更好时，还会产生一个较一级彩虹暗得多的二级彩虹，它的张角约51度，但是颜色的排列顺序与一级彩虹正好相反。

白天，彩虹圆弧所在圆的圆心被称为“对日点”，它是天空中与太阳正好反向的那个点，因此也就是你头部的影子所在的方向。既然太阳位于地平线之上，这个点当然远在地平线之下。晚上，这个几何关系仍旧成立，只是那个月亮彩虹



2005年5月22日当地时间晚上11点，Kim Steinbacher在下约塞米蒂瀑布的底部附近架起三脚架，拍下了这幅双月虹的美景。尽管雾气和水花从瀑布上飞溅而下，她还是设法在长时间的曝光中避免了镜头被打湿。

这幅Brent Gilstrap于2006年5月15日当地时间1：20，摄于Sentinel桥（距离瀑布主观察点约823米）旁边停车场的风景照片，呈现出别具一格的月虹倒影。这个影像是由3张曝光30秒和1张曝光60秒（针对下部倒映区）的照片组合而成。约塞米蒂国家公园在随后这个冬天的下雪量达到了平常的两倍。

的圆心要被称为“对月点”了。

长时间的曝光表明，月亮彩虹的色彩模式同样是存在的。人的肉眼在昏暗的光线下会丧失对色彩的分辨能力，所以肉眼观测者通常会把月虹描述成灰色、白色或银色。但在理想的条件下，例如明澈的空气、丰富的水滴以及接近满月时的明亮月光，有些人也能够在肉眼观察中看到月虹的色彩。

马克·吐温和月虹

在1872年的游记《艰苦历程（Roughing It）》第71章中，马克·吐温描述了他在1866年前往夏威夷途中经历的一次观察：

为什么库克船长不将他的伟大发现称为彩虹岛呢？这个令人惊讶的景观在岛上随处可见，不仅每天可见，甚至有时在夜间也会出现。那不是我们通常见到的银色月虹，而是明亮且带有色彩，就像太阳和雨的孩子一样。我在几天之前就曾看到过这样的景象。

这位受人尊重的作家1879年从欧洲返回美洲时，再次邂逅了这一近乎完美的奇观。他在1879年8月31日的日记本中记录下他所看到的现象。

在“高卢”的海上，……大约晚上9点的明月，宁静的大海，一场壮丽的月亮彩虹……一个完整的弧形，展现出的色彩就像在白天一样壮观。有人说它并没有那么灿烂，稍微暗淡了一点……但在我看来，它与白天的彩虹实在没有什么分别。

吐温也认为他自己十分幸运，能够在一生之中看到两次如此壮观的景象。

本·富兰克林在海上

另一个在海上见到月虹的记录来自本杰明·富兰克林，那时他是在1726年从伦敦返回费城的途中。他的日记上记录的日期是儒略日8月30日，相当于格里历（也就是现在使用的公历——译者注）的9月10日。他这样写道：

风停止了，这个晚上的月亮在8点后升起时几乎满月。在西方的云层那里似乎有一道彩虹，这是我第一次在晚上看到由月亮引起的彩虹。

天文学家们在富兰克林的游记中还找到了诸如日偏食之类天象的有趣记录。就在上述那个记录之后两个星期，他就又观察到了一次月偏食。

2005年9月，本文作者们利用量尺、铅垂和激光水平仪对下约塞米蒂瀑布主观测点附近的地形进行测量。自左向右分别为 Kellie Beicker，Russell Doescher 和 Don Olson(左图)。与《天空与望远镜》的高级编辑 Roger Sinnott（左）一起测定地平方向，以及与瀑布底部的距离。Ashley Ralph在右边(中图)。Olson 和 Doescher一起策划如何在夜间拍摄瀑布区的星空照片(右图)。

月虹和瀑布

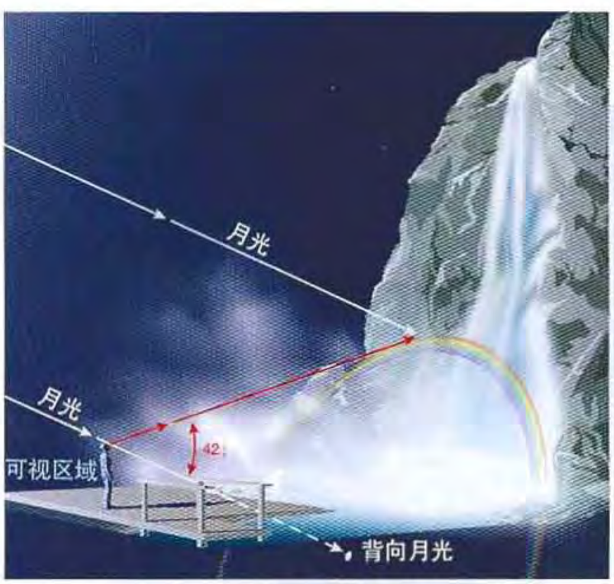
除了雨后的月夜，在大型瀑布的附近，我们也能找到月虹的身影。在赞比亚和津巴布韦交界处的维多利亚瀑布区，旅游公司提供了一种名为“月虹之旅”的观光项目。而在肯塔基州的坎伯兰瀑布区，也有一些观察月虹的公众活动。早期的明信片还曾用这个瀑布附近的一个名为“月虹小居”的宾馆做主题。著名的尼亚加拉大瀑布在设置人工照明系统之前，月虹也曾是一道十分吸引人的景致，当地的两个地名（月亮岛和月亮瀑布）都是因这个现象而得名的。

缪尔和约塞米蒂的月虹

约塞米蒂国家公园的创立者之一，博物学家约翰·缪尔（John Muir）如此描写瀑布边的月虹。

奔腾而下的飞流边，四溅的水雾是月虹经常

对于下约塞米蒂瀑布的观察者而言，当对月点方向和水雾方向的夹角接近42度时，就会出现月虹。月光并不需要照射在观察者的身上，但必须照射在瀑布的水雾之上。



箭头指向为下约塞米蒂瀑布的主观赏区，即约塞米蒂溪流上一座木桥西端的平台。这个欣赏和拍摄月虹都十分理想的观察点，距离瀑布底部为165米。

出没之处。它们的颜色几乎与阳光下的彩虹完全一样，只是在鲜艳程度上略逊一点。在上约塞米蒂瀑布的脚下，只要有足够的月光和充足的水量，几乎每个晚上都可以欣赏到这个景象。宏大的彩虹呈现在如雷般的瀑布之中，有时甚至能够看到二级彩虹的存在。

在1912年出版的著作《约塞米蒂》中，缪尔极力怂恿游客在夜间来探索约塞米蒂峡谷，因为同时还能观赏到月虹美景。

气势恢宏，五颜六色的野性飞虹，其形状如此美丽，再加上雷鸣般奔泻而下的巨大瀑布，这是山野奇趣中给人印象最为深刻的景观了。

夜幕降临的时候，独自站立在峡谷北部边缘附近的缪尔常常为这个魔幻般的景象所陶醉。

月光洒落下来……我看到了一个完美的瀑布飞虹，美丽而清晰的色彩……美妙的弧形下面是纯白色的水气波浪汹涌，就像在夜间跳舞的精灵。

缪尔在1871年4月给Jeanne S. Carr夫人的信中写道："银色的月亮照亮了这个我们称之为'瀑布'的造化之物，产生了两道令人惊叹的彩虹，绸缎般的瀑布衬托在它的背后，还可以看到一些星星闪烁于彩弧之中。

受到缪尔的感召，我们决定编写一段计算机程序，来预测什么时候能够在约塞米蒂的瀑布那里看到月亮彩虹。

错过2005的月亮彩虹？

在一个名为"Calphoto"的专门收集加州风景照的雅虎讨论组中搜索与月虹有关的信息时，我们遇到了一次小的意外，也从中更了解到我们的程序预测有多么重要。

2005年6月22日晚上，月亮达到了完全满月的98%。大约50位摄影爱好者们集中在下约塞米蒂瀑布的附近，等候月虹的出现。当夜幕降临，温度几乎降到了冰点，瀑布上飘下来的水雾使得周围再也没有什么地方能够独保干燥。一直等候到半夜，月虹没有出现，等候者们终于在失望中散去了。

在第二天的讨论中，小组成员们十分奇怪，为什么在"一切条件都具备"的情况下月虹竟然会失约。有一条信息是这样结尾的："是什么使我们错过了这独一无二的美景？"

计算月虹的可见性

我们认识到，要确保在下约塞米蒂瀑布区看到月虹，必需同时满足6个条件。头两个条件依赖于天气，而后面4个条件则与天文因素有关，这些可以用计算机程序来模拟。

月亮附近的天空晴朗明澈。

维多利亚瀑布水雾形成的壮丽月虹，其背后闪烁的是猎户星座。Calvin Bradshaw在从澳大利亚布里斯班前往非洲访问时拍摄了这一美景。

2004年5月4日，Rob Ratkowski在夏威夷Maui岛Kahului的西方天空，捕捉到了这幅同时展现月虹、恒星和三颗行星的精彩照片。在摄影者的背后，一轮明月正升起在东方空中。在西边，最亮的天体是金星，几乎位于月虹的中间，靠近它的是金牛座β星，金星的上面和左面分别为火星（在月虹里面）和土星（在月虹外面，所在背景为双子座）。

在瀑布的底部有足够的雾气和四溅的水花。因此在约塞米蒂观赏月虹的最佳时间应该是冰雪融化的时节，也就是4月、5月或6月，有时也可能延续到7月上旬。

天空足够黑暗。在我们的程序中，要求太阳应该处于地平线以下至少9度。

明亮的月光。月亮的亮度取决于它的位相、与地球的距离以及所处的地平高度。我们的程序要求月光应亮于以下临界条件：地平高度25度，与地球的距离为地－月平均距离，位相为完全满月的95%。

月光没有被山或岩石所遮挡。为了使月光能够照射在下瀑布之上，月亮的位置必须高于附近的山峰或建筑物。为了确定当地地平线的轮廓，我们必须前往约塞米蒂，实地拍摄很多周围景物的照片。

准确的空间几何关系。下约塞米蒂瀑布的观赏区位于约塞米蒂溪流山一个木桥的西端。从这个地点看去，只有当对月点与瀑布底部的角度近似于42度才可能出现月虹。为了真正搞清楚其中的几何关系，我们也必须前往约塞米蒂实地勘察。

约塞米蒂之旅

幸运的是，我们的德州讨论组恰好已经安排了一个前往约塞米蒂的计划。我们做出预测，2005年9月15日那天，月亮的位置将使得摄影家Ansel Andams在冰川角所摄的著名作品展现的美景再现。预报是成功的，数以百计的摄影爱好者蜂拥而至，而我们却把大量的时间花在了下约塞米蒂瀑布区。

9月的水流已经成了涓涓细流，这恰好满足了我们的需要，因为我们可以直接站在瀑布的脚下了。这在春天时瀑布那种雷鸣般奔涌的状态下是不可能的。我们在夜里拍下了以灿烂群星为背景的附近的山峰，已知星星的高度和方位角有助于我们精确地描绘出当地地平线的结构。

白天，我们利用尺子、铅垂和激光水平仪进行了传统测量工作。网络资料告诉我们下约塞米蒂瀑布距离观察点为约92米，实测结果却是165米。我们还确定了两个重要的角度值。一个人站在观察平台的中央时，可以在方位角325度（也就是北偏西35度）方向看到水雾最密的地方，向上的仰角则为12度。

2007年下约塞米蒂瀑布的月虹预测			
夜间观测日期	（2007年）	太平洋夏令时（PDT）	月相
4月29日	（星期日）	8:32 p.m.（周日）－9:20 p.m.（周日）	96%
4月30日	（星期一）	8:33 p.m.（周一）－10:40 p.m.（周一）	99%
5月1日	（星期二）	10:05 p.m.（周二）－11:50 p.m.（周二）	100%
5月2日	（星期三）	11:25 p.m.（周三）－1:00 p.m.（周四）	99%
5月3日	（星期四）	12:37 a.m.（周五）－2:00 p.m.（周五）	96%
5月29日	（星期二）	9:10 p.m.（周二）－10:50 p.m.（周二）	97%
5月30日	（星期三）	10:26 p.m.（周三）－11:50 p.m.（周三）	99%
5月31日	（星期四）	11:33 p.m.（周四）－12:55 a.m.（周五）	100%
6月1日	（星期五）	12:39 a.m.（周六）－1:50 a.m.（周六）	98%
6月28日	（星期四）	10:35 p.m.（周四）－11:25 p.m.（周四）	98%
6月29日	（星期五）	11:30 p.m.（周五）－12:20 a.m.（周六）	100%
6月30日	（星期六）	12:20 a.m.（周日）－1:05 a.m.（周日）	99%
7月1日	（星期日）	12:55 a.m.（周一）－1:45 p.m.（周一）	96%

注：所有的计算都是基于主观测点，即下约塞米蒂瀑布底部附近木桥西端的平台。

至此，我们已得到了所有需要的信息。

错过月虹的原因找到了！

以下这个例子可以帮助我们解释其中的几何关系。2005年6月23日太平洋夏季时（PST）的凌晨1：30，一轮几乎正圆的明月已接近于约塞米蒂峡谷的正南方，方位角169度，高度23度。三角关系表明对月点（方位角＝169＋180＝349度，高度＝－23度）与瀑布底部最密集处的角度正好为42度。产生月虹的条件非常理想。

假定雾气占据的范围较大，包括了从瀑布最密集处向上约8度和向下约5度的地方，那么我们的程序计算表明在12：45至2：00之间将能看到月虹。随着月亮逐渐升高和向西移动，月虹应首先出现在瀑布的顶部，然后慢慢地向下和向东飘移。

我们现在可以对2005年6月22日晚的令人沮丧的遭遇做出解释了。其实月虹的确出现了，但出现的时间却迟至第二天的凌晨！我们由此认识到，对出现月虹准确日期和时间的预测将有助于人们避免长时间在寒冷潮湿的环境中翘首以盼地等待。

2006年和2007年

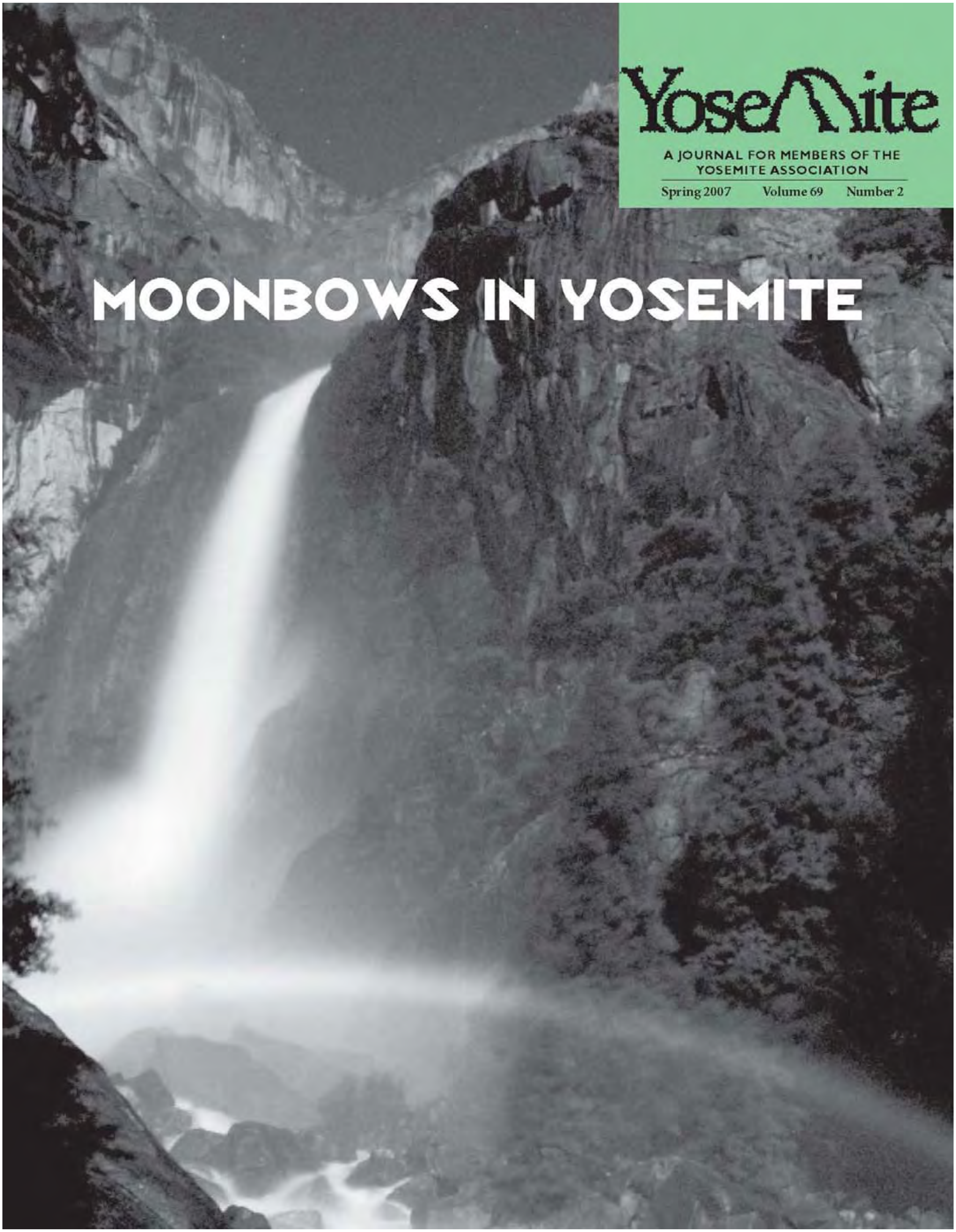
在2006年融雪的季节里，我们为检验程序，计算得出了一张预测表格，并将其寄往Calphoto观测摄影组和其他有兴趣的摄影者，摄影结果证实了我们计算的正确性。

我们的程序在融雪季节里每一次月圆前后都预测了4次～5次月虹。这可能有一点保守，但它和缪尔的判断基本一致，"显著的月虹一般发生在4月、5月、6月，有时迟至7月中的几天里。"

并不是只有暴雨和瀑布才能发生这个现象。其实任何人都可以用花园里的喷水龙头创造出一个月虹来。当明月高照之时，朝向与你的头顶影子方向成42度角的地方喷出雾气。月虹在黑暗背景（例如灌木丛或是墙壁等）的衬托下将更容易看见。一旦你亲眼所见，那美妙的银白色月虹的景象定会让你终身难忘。

——译自《天空与望远镜》（2007年5月号）

（责任编辑：吕璘）


Yosemite
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MOONBOWS IN YOSEMITE

BY DONALD W. OLSON, RUSSELL L. DOESCHER, AND KELLIE N. BEICKER

MOONBOWS IN YOSEMITE

Observers of nature as far back as Aristotle knew that a bright Moon, like the Sun, could produce the phenomenon known as a moonbow:

> *The rainbow occurs by day, and it was formerly thought that it never appeared by night as a moon rainbow. This opinion was due to the rarity of the phenomenon: it was not observed, for though it does happen, it does so rarely.... The colors are not easy to see in the dark .... The moon rainbow appears white....*
>
> *Meteorologica*, circa 340 B.C.

MOONBOWS AND WATERFALLS

Most observers find moonbows in the spray near waterfalls. At Victoria Falls, on the border between Zambia and Zimbabwe, tour companies offer "Lunar Rainbow Tours." Moonbow observing is also popular at Cumberland Falls in Kentucky; early postcards show a hotel named the Moonbow Inn adjacent to the falls. Lunar bows were a great tourist attraction at Niagara Falls in the years before the installation of artificial night lighting, and two topographic features there (Luna Island and Luna Falls) are named for the phenomenon.

The full palette of colors is present in lunar rainbows, though the spectrum is often lost to human observers. Because the human eye loses most of its color sensitivity in dim light, moonbows are usually described as gray, white, or silver. But under ideal conditions–clear air, an abundant spray of droplets, and bright moonlight–the colors in lunar rainbows (which have been confirmed by time exposure photographs) can shine through.

MUIR AND YOSEMITE MOONBOWS

In his 1912 book, *The Yosemite*, John Muir eloquently described such an observation:

> *Lunar rainbows or spray-bows also abound in the glorious affluence of dashing, rejoicing, hurrahing, enthusiastic spring floods, their colors as distinct as those of the sun and regularly and obviously banded, though less vivid. Fine specimens may be found any night at the foot of the Upper Yosemite Fall, glowing gloriously amid the gloomy shadows and thundering waters, whenever there is plenty of moonlight and spray. Even the secondary bow is at times distinctly visible.*

Muir would climb up to a ledge near Upper Yosemite Fall to look for the moonbow:

> *This grand arc of color, glowing in mild, shapely beauty in so weird and huge a chamber of night shadows, and amid the rush and roar and tumultuous dashing of this thunder-voiced fall, is one of the most impressive and most cheering of all the blessed mountain evangels.*

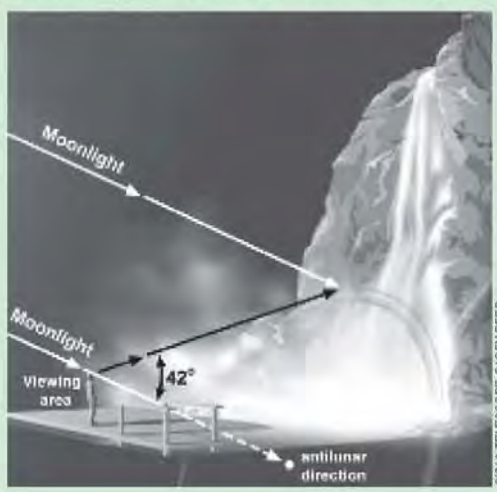
Another of Muir's favorite climbing destinations at the time of a full Moon was the edge of a gorge where

RAINBOW SCIENCE

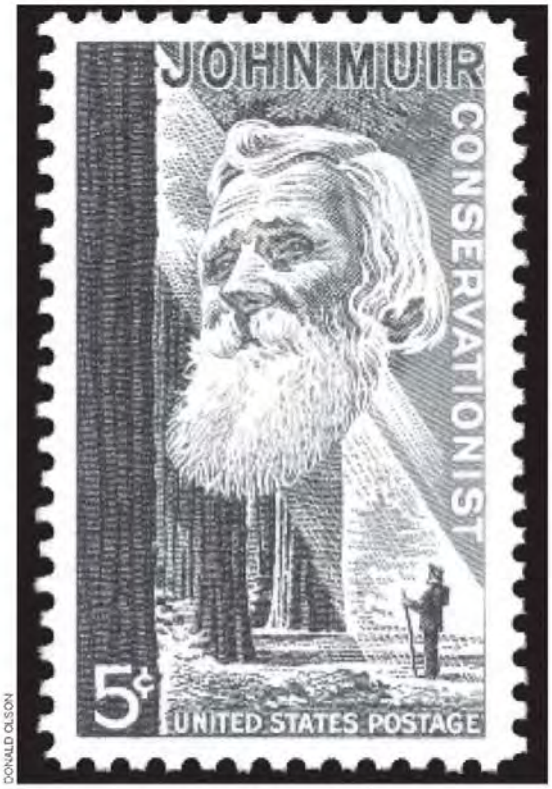
When sunlight shines on fine droplets of water, a combination of refraction and internal reflection causes the rays to separate into different wavelengths, as though split by a prism. The light ray changes direction three times: first, by bending when it enters the drop and passes from air to water; second, by reflecting off the back of the drop; third, by bending as it leaves the drop and passes from water back into air. The resulting arc of colored light forms a rainbow. The display most commonly seen is known as the primary rainbow; this forms a circular arc with a radius of 42 degrees. Under good conditions, a much fainter secondary bow can appear outside the primary rainbow. This will have a radius of 51 degrees and the sequence of colors will be reversed.

By day the center of the rainbow is the *antisolar point*, the point exactly opposite the Sun. It is located as far below the horizon as the Sun is above the opposite horizon. The center for a lunar rainbow, the *antilunar point*, has the same geometry but is located exactly opposite the Moon. These points are useful for calculating where solar rainbows and moonbows are most easily seen.

For an observer at the Lower Yosemite Fall viewing area, a moonbow can appear only when the angle between the antilunar point and the direction of the spray is approximately 42 degrees. The Moon need not shine on the observer, but must shine on the spray.



SKY & TELESCOPE, CASEY REED



DONALD OLSON

John Muir, commemorated in this 1964 postage stamp, was an enthusiastic Yosemite moonbow observer.

MOONBOW CONDITIONS

1. **Clear sky**
2. **Abundant mist and spray at the base of the fall**
   The best moonbows at Yosemite occur during peak snowmelt runoff, from April to June and sometimes early July.
3. **Dark sky**
   The Sun should be more than 9 degrees below the horizon, ending bright twilight.
4. **Bright moonlight**
   The brightness of the Moon depends on its phase, distance from Earth, and altitude above the horizon. The minimum brightness conditions considered by the program correspond to a Moon at an altitude of 25 degrees, at its mean distance, and with an illuminated fraction of 95%.
5. **Unobstructed moonlight**
   For moonlight to strike the spray at the base of Lower Yosemite Fall, the Moon must be above the nearby mountains, domes, and cliffs.
6. **Correct rainbow geometry**
   The Lower Yosemite Fall viewing area is a paved terrace at the west end of a wooden bridge over Yosemite Creek. From here, a moonbow will appear only when the angle between the antilunar point and the direction toward the base of the fall is near the rainbow angle of 42 degrees.

he could view smaller intermediate falls on the plateau between Upper and Lower Yosemite Falls:

> *...the moonbeams were pouring through...I saw a well-defined spray-bow, beautifully distinct in colors...while pure white foam-waves beneath the beautiful bow were constantly springing up out of the dark into the moonlight like dancing ghosts.*

By the time he published this book, Muir had been observing moonbows for more than four decades. In an April 1871 letter to Mrs. Jeanne S. Carr, he wrote:

> *Silver from the moon illumines this glorious creation which we term "falls," and has laid a magnificent double prismatic bow at its base. The tissue of the fall is delicately filmed on the outside like the substance of spent clouds, and the stars shine dimly through it.*

COMPUTING MOONBOW VISIBILITY

Inspired by Muir's dramatic accounts, we decided to write a computer program to predict the dates and times when moonbows should appear. Six conditions are required for a moonbow to be readily visible. The first two are weather-dependent, but the remainder require astronomical conditions that can be modeled by computer. Our program forecasts optimal moonbow viewing times for the area near the base of Lower Yosemite Fall.

TRIP TO YOSEMITE

Ascertaining the profile of the local horizon and the geometry of the viewing area relative to the falls required a visit to the site. Fortunately, our research group had already scheduled a trip toYosemite. In an article in *Sky & Telescope* magazine, we predicted that on September 15, 2005, the Moon's position would recreate the scene in *Autumn Moon*, a famous Ansel Adams photograph from Glacier Point. The moonrise event was a great success, with hundreds of photographers in attendance, but we spent most of our time in the park near Lower Yosemite Fall.

That September, the flow of water was little more than a trickle. This worked to our advantage. We could stand right at the base of the fall, something that would be impossible in the thundering torrents of the spring runoff season. We took night photographs of the nearby mountains and cliffs silhouetted against brilliant star fields. The images allowed us to accurately trace the profile of the horizon.

By day we did conventional surveying with rulers, plumb bobs, and a laser level. Websites indicated that Lower Yosemite Fall would be about 100 yards from the viewing area, but our survey found this distance to be 180 yards. We also determined the precise angles (azimuth and altitude) of the direction of view from the terrace to the densest part of the spray near the base of the fall. With information in hand, we returned home to finish writing our moonbow program.

MOONBOW FORECAST

During the snowmelt runoff season of 2006, we circulated the program's predictions to interested photographers. The photographic results verify the accuracy of our method.

The accompanying table gives our moonbow predictions for 2007. The calculations of dates and precise times can help visitors avoid long waits in a location that can be cold and wet with blowing mist. Our website, http://uweb.txstate.edu/~do01/, contains more detailed descriptions of the position of the Moon and appearance of the moonbows.

MOONBOW PREDICTIONS FOR LOWER YOSEMITE FALL

Calculations are for the terrace at the west end of the wooden bridge near the base of Lower Yosemite Fall.

DATE IN 2007	TIMES (Pacific Daylight Time)	LUNAR PHASE
April 29 (Sun)	8:32 p.m. (Sun) to 9:20 p.m. (Sun)	96%
April 30 (Mon)	8:33 p.m. (Mon) to 10:40 p.m. (Mon)	99%
May 1 (Tues)	10:05 p.m. (Tues) to 11:50 p.m. (Tues)	100%
May 2 (Wed)–May 3 (Thurs)	11:25 p.m. (Wed) to 1:00 a.m. (Thurs)	99%
May 3 (Thurs)–May 4 (Fri)	12:37 a.m. (Fri) to 2:00 a.m. (Fri)	96%
May 29 (Tues)	9:10 p.m. (Tues) to 10:50 p.m. (Tues)	97%
May 30 (Wed)	10:26 p.m. (Wed) to 11:50 p.m. (Wed)	99%
May 31 (Thurs)–June 1 (Fri)	11:33 p.m. (Thurs) to 12:55 a.m. (Fri)	100%
June 1 (Fri)–June 2 (Sat)	12:39 a.m. (Sat) to 1:50 a.m. (Sat)	98%
June 28 (Thurs)	10:35 p.m. (Thurs) to 11:25 p.m. (Thurs)	98%
June 29 (Fri)–June 30 (Sat)	11:30 p.m. (Fri) to 12:20 a.m. (Sat)	100%
June 30 (Sat)–July 1 (Sun)	12:20 a.m. (Sun) to 1:05 a.m. (Sun)	99%
July 1 (Sun)–July 2 (Mon)	12:55 a.m. (Mon) to 1:45 a.m. (Mon)	96%

The program typically predicts moonbows on four or five nights near each full Moon during the snowmelt runoff period. While conservative, these predictions generally agree with the conclusions of sharp-eyed John Muir, who judged that:

> *...magnificent lunar bows may be found for half a dozen nights in the months of April, May, June, and sometimes July.*
>
> John Muir, *"Yosemite in Spring," New York Tribune,* May 7, 1872

Rain showers and waterfalls are not the only settings where this phenomenon occurs. Anyone can make a moonbow with an ordinary garden hose. With a bright Moon high in the sky behind you, direct a fine mist toward a spot 42 degrees away from the shadow of your head. It will be much easier to see the moonbow against a dark background such as a bush or wall. Once seen, the ethereal silver-white of the moonbow is not easily forgotten.

Don Olson and Russell Doescher teach physics at Texas State University; Kellie Beicker is a student in the university's Mitte Honors Program. The authors have published four Yosemite-related articles in* Sky & Telescope: *"Dating Ansel Adams's* Moon and Half Dome*" (December 1994); "Ansel Adams and an* Autumn Moon*" (October 2005); "An Ansel Adams Encore" (January 2006); and "Moonbows over Yosemite" (May 2007), upon which this article is based.

Texas State Mitte Honors Students Help Unravel the Mystery of Moonbows.

Rainbows at night? They do exist – albeit elusive and rare. Moonbows, or lunar rainbows, are a little-known natural phenomenon that can be breathtaking under the right conditions. In fact, famed naturalist John Muir once urged visitors to Yosemite National Park to seek the ethereal moonbow at night in Yosemite Valley.

Left-to-right: Russell Doescher, Kellie Beicker, Sky & Telescope senior editor Roger Sinnott, Ashley Ralph, Don Olson. (Photo by Marilynn Olson)

Now, a team of astronomers from Texas State University-San Marcos has applied a unique brand of forensic astronomy to the rainbow's nocturnal cousin, unraveling when and where this phenomenon can best be viewed in the remote California wilderness.

Texas State physics professors Donald Olson and Russell Doescher, along with Mitte Honors students Kellie Beicker, Ashley Ralph and Hui-Yiing Chang, published their findings in the May 2007 edition of Sky & Telescope magazine.

Although people have been watching for moonbows for centuries, this is the first time anyone has calculated dates and precise times for appearances of this unusual event.

Conditions must be ideal for moonbows to form, including a bright moon and abundant water droplets suspended in clear air. Figures from Aristotle to Benjamin Franklin have written about the rare phenomenon, and as early as 1871, Muir wrote enthusiastically that moonbows could often be seen in the fine spray coming off Yosemite Falls – no rain clouds required. He described their beauty in his 1912 book, The Yosemite.

The Texas State researchers, inspired by Muir's accounts of the spectacle, developed a computer program which would allow the accurate prediction of dates and times favoring the appearance of moonbows at the Yosemite waterfalls.

The research team quickly established the following six criteria necessary for Yosemite moonbows to form and which they modeled with their software:

1. clear skies around the moon
2. abundant mist at the base of the falls
3. dark skies
4. bright moonlight
5. moonlight not blocked by mountains
6. correct rainbow geometry

Determining the precise topography and geometry to satisfy the final two criteria in the program required on-site research, and in September of 2005 the Texas State group traveled to Yosemite.

The resulting data gained from extensive surveying and on-site topographical research paid off immediately. Upon return to Texas, Olson and his team discovered why a moonbow anticipated by photographers on the evening of June 22, 2005 failed to appear, despite apparently perfect conditions. Olson realized that the moonbow did in fact appear, but not until 12:45 a.m., long after the photographers had given up and gone home for the night, thus proving the value of the Texas State predictive model.

The group's work has been featured in publications ranging from the Los Angeles Times to the Journal of the Yosemite Association, and their predictions have been tested by eager photographers traveling to the Yosemite Valley – with spectacular results.

Moonbow predictions for the remainder of 2007 along with additional information on the positions of the moon and factors involved in the formation of moonbows can be found online at http://uweb.txstate.edu/~do01/.

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Meteorite studies suggest that winds from a nearby massive star – not a supernova explosion – triggered the birth of our solar system

NEW SCIENTIST SPACE BLOG

Somewhere over the moonbow

A new program predicts when the geometry is right to view 'moonbows' at Yosemite Falls

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Thursday, May 24, 2007

Somewhere over the moonbow

Everybody knows the crucial ingredients needed to make a rainbow: sunshine and rain. But those are just the most familiar kind – rainbows appear anytime white light passes through water droplets, if the viewing geometry is right.

Moonbows, for example, are made from moonlight and drops of water, and the mist generated by waterfalls provides a perfect medium to produce them. Rainbows at waterfalls are a common sight in daytime, and moonbows can also grace the mist on favourable nights.

A trip to try to catch a glimpse of a moonbow can end in disappointment if the moonlight is not hitting the mist at the right angle for the moonbow to be visible. But a team led by Texas State University astronomer Don Olson recently created a computer program that predicts when the geometry will be just right at one ideal moonbow site – Yosemite Falls in California, US. They have created a moonbow forecast website for Yosemite.

Using the predictions, professional photographer Brent Gilstrap recently captured a spectacular view of a Yosemite Falls moonbow (see image).

Because moonlight is so much dimmer than sunlight, the colours can be harder to see. But long exposure photographs like Gilstrap's bring them out beautifully. If you have ambitions to take your own moonbow picture, you can visit this site for tips on how to do it.

David Shiga, Online reporter (Image: Brent Gilstrap)

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EARTH

By Beth Geiger

A U.S. astronomer devises a formula for finding nighttime rainbows in Yosemite National Park.

OVER THE MOONBOW

One moonlit night about a century ago, naturalist John Muir watched as a luminous arc appeared in the spray over Lower Yosemite Fall in California. In subsequent years, Muir saw more of the arcs, which he described as "glowing gloriously amid the gloomy shadows and thundering waters." What Muir had witnessed were *moonbows*—rainbows lit by moonlight instead of sunlight.

Inspired by Muir's description, many people have spent long nights watching Lower Yosemite Fall, hoping to glimpse the same sight. However, Yosemite's lovely moonbows are as elusive as shooting stars in daylight. And moonbow watching can be a real endurance test at the fall. It's dark, cold, and wet, wet, wet there. "When the fall is really kicking, it's like a car wash," says Keith Walklet, a Yosemite-area photographer.

Don Olson, a professor of physics at Texas State University, had visited Yosemite National Park to research photographs taken there by the great Ansel Adams. Intrigued by the difficulty people had finding moonbows, Olson wondered whether a bit of astronomical ingenuity could help. Many elements, he knew, must come together before a moonbow appears. Could he calculate the exact date and time when all the right conditions coincide at Lower Yosemite Fall?

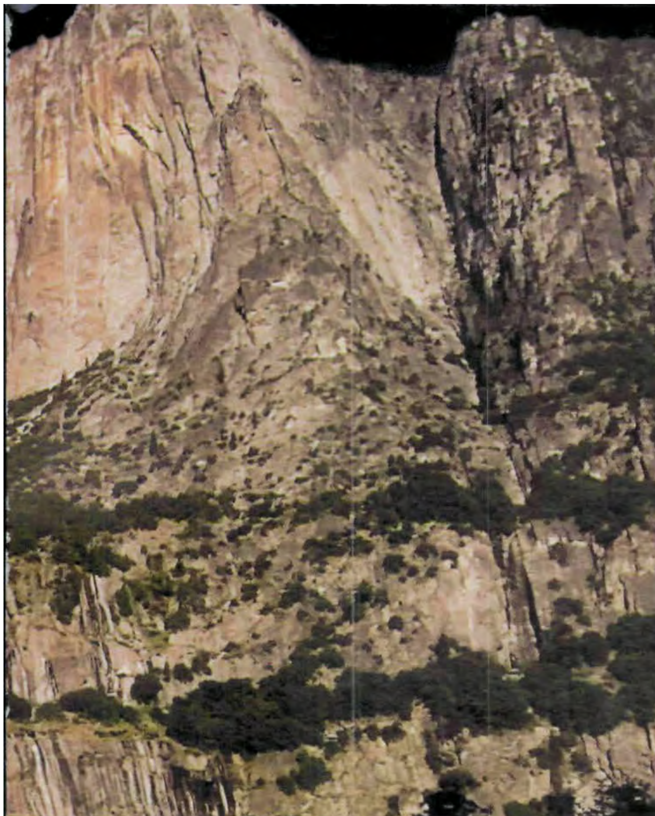
MOONLIGHT, SHINE BRIGHT

The first condition Olson considered for his calculation was moonlight. To cast enough light for a moonbow, the moon must be bright. A bright moon means a full moon, so Olson narrowed his search to those dates when the moon would be at least 95 percent full.

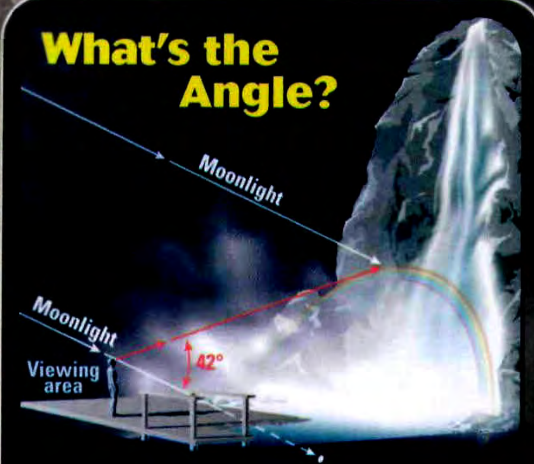
Being full isn't the only condition that makes the moon really glow, however. It should also be near *perigee*, the point where it orbits closest to Earth. (The moon's orbit is not circular; it's *elliptical*—egg-shaped.) By contrast, *apogee* is the point where the moon is farthest from Earth. "Moonlight is roughly 25 percent to 30 percent brighter at perigee compared to the same lunar phase near apogee," says Olson. That condition further narrowed Olson's search.

Olson also knew that the moon must be relatively low in the sky. Moonbows (and rainbows) appear only when the geometry is right. The direction of the light, the location of the fall, and the observer's line of sight

Top: Brent Gilstrap; Sidebar: Graphic: Casey Reed/*Sky & Telescope*; Photo: Chris Dunstan



What's the Angle?



A moonbow (or rainbow) will appear to a person on the viewing terrace at Lower Yosemite Fall only when the moon (or sun) is at the viewer's back. Even then, the moonbow will materialize only when the direction of the moonlight, the location of the moisture that *refracts* (changes the angle of) the moonlight, and the observer's line of sight create an angle of about 42 degrees. This diagram shows how that angle is measured. What happens to the angle as the moon rises into the sky?

An aerial view of Lower Yosemite Fall and a bridge at its base

must form a certain angle. (See "What's the Angle?") At that angle, colors are most likely to split out of the light into a moonbow (or rainbow) of hues.

Olson had another astronomical condition to consider. Moonbows are faint to start with. Like distant stars, they don't show up until the sky is really dark. Olson further limited his search to those times when the sun was at least 9 degrees below the horizon, pulling the daylight out of the sky along with it.

LOCATION, LOCATION

With critical moon phases and angles determined, Olson then customized his predictions to fit Yosemite Park. "It would be embarrassing to predict a moonbow for a certain time and then discover that the moon was hidden behind a mountain and not shining on the waterfall," he says.

At Lower Yosemite Fall, everyone watches for moonbows from a viewing terrace 165 meters (540 feet) from the base of the waterfall. "We carefully photographed and mapped in three dimensions all the *topographic* [surface] features near Yosemite Fall," says Olson.

After that, one final condition remained: the amount of moisture in the air opposite the moon. Some moonbows appear during rainstorms, but Yosemite's moonbows depend instead on a steady stream of mist from the waterfall. When does the fall gush with enough water? Olson narrowed his search to the spring snowmelt months.

With all the factors identified, Olson plugged them into a computer program and came up with a series of dates and times. He then had local photographers field-test the results. He also posted the results on the Internet. The reports came back: His predictions were good.

"We've had terrific response," he says. "Before this, people would basically go out in the full moon and hope for the best."

"I wouldn't have had a clue," agrees photographer Brent Gilstrap.

Walklet is also pleased. "Using Don's charts, we're as happy as clams," he says.

When will a vivid moonbow most likely occur at Lower Yosemite Fall this year? If no rain is falling and the fall is running at top volume, the date will be April 18, 2008, between 8:30 and 11:30 p.m. See you there! **CS**

Chasing moonbows goes high tech

Texas State University team produces a computer model to predict elusive phenomenon

By ERIC BAILEY
LOS ANGELES TIMES

YOSEMITE NATIONAL PARK, CALIF. — Aristotle took note of this celestial happening a couple of millennia back. Ben Franklin bagged a sighting or two, as did Mark Twain. The venerable John Muir, chronicler of Sierra mountaintop and meadow, waxed enthusiastic about the nighttime phenomenon.

The hunt for the elusive "moonbow" has long been a nocturnal lure for dreamy hikers, insomniac seamen and intrepid photo buffs. But in the past, seeing one of these nighttime rainbows — caused when a full moon's rays bounce off the mist of a departing rain cloud or raging waterfall — has been dictated mostly by chance.

No longer.

A team of astronomers from Texas State University in San Marcos has produced a computer model that can reliably predict the date and duration of moonbows at Yosemite Falls, the national park's tallest and most photogenic waterfall.

Their predictions have sent waves of camera buffs and Yosemite Valley visitors trekking up the trail to the plank bridge near the base of the waterfall.

Aside from those who have visited during an overcast night, few have come away disappointed.

"So far as we know, we're the first to predict dates and precise times for when moonbows will appear," said Don Olson, the Texas State astronomy professor who led a team of honors students in the project. "It's great for people who otherwise might have sat around all night waiting to see a moonbow, and for the students it was a nice exercise in calculus, spherical trig and computing."

The team's moonbow table took Brent Gilstrap to the waterfall one recent night.

Gilstrap, who two years ago chucked his computer software career to become a commercial landscape photographer, has been dependably making spectacular shots of moonbows ever since he learned of the Texas State lunar table.

What may be his most remarkable moonbow photo came not at the fall's base but across the valley on a cloudless night last year. Gilstrap caught a broad panorama: the entire Yosemite Falls cascading down with a moonbow arching across mist halfway up the sheer cliff face, the whole scene reflected in mirrored waters of a flooded meadow.

On a recent and far less perfect night, the moon was dodging in and out of a gauzy bank of high clouds preceding a spring storm that hit the next day. By 10 p.m. the moonbow was a ghostly arch floating above the creek's granite rubble.

"Honestly, it was pretty lousy until a few minutes ago," Gilstrap yelled above the roar of the waterfall, his parka whipping in the rush of wind and mist coursing down the gorge.

At any one time during the course of the evening, a dozen people paused to take in the nighttime spectacle.

John Wolfarth, visiting from Boston, wasn't disappointed.

"Oh, there it is! There it is! There it is!" he yelled to his friend Kevin Powers. "That's amazing!"

Bruce Wang, a 28-year-old student from the University of California, San Francisco, had driven from the Bay Area to photograph the moonbow. He spent hours making moonbow shots with his tripod-mounted camera, then at 11 p.m. packed up to head home.

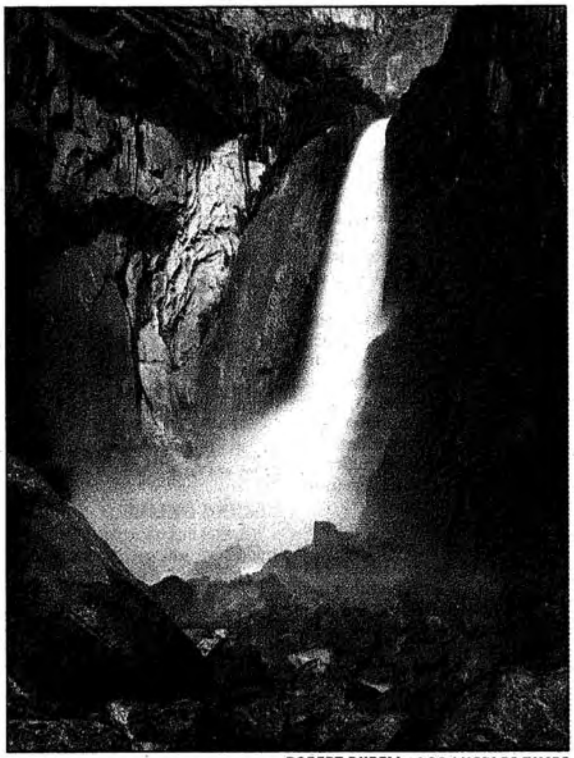
Olson said he had had long been mulling a project to create a table tracking moonbows' appearances.

The opportunity presented itself in 2005, when he and Texas State University lecturer Russell Doescher arrived in the valley with a team of students.

With the water low, they could venture into the creek bed below Yosemite Falls to make the measurements needed to plot important factors for moonbow observations, including the true horizon of Yosemite Valley's southern cliffs, which can block a moonrise.

Back at the university, Olson, Doescher and students Kellie Beicker, Ashley Ralph and Hui-Yiing Chang, from the school's Mitte Honors program, crafted a computer model factoring in the various earthbound and celestial coordinates. They conducted real-world tests in 2006 that proved their calculations were spot on.

A little luck is still needed. A good moonbow requires clear sky, abundant mist at the base of the fall and an absence of artificial light.



ROBERT DURELL : LOS ANGELES TIMES

NOCTURNAL SIGHTING: A moonbow forms at Yosemite Falls. Ideal conditions for moonbows include clear skies, abundant mist at the base of a waterfall and the absence of artificial light.

ONLINE

- **Schedule:** The schedule of moonbows can be found online at uweb.txstate.edu/~do01/.
- **Photos:** Brent Gilstrap's moonbow photographs are online at groundhog.smugmug.com/gallery/1036309/1/69899911/Original.

Los Angeles Times

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Tuesday, May 22, 2007

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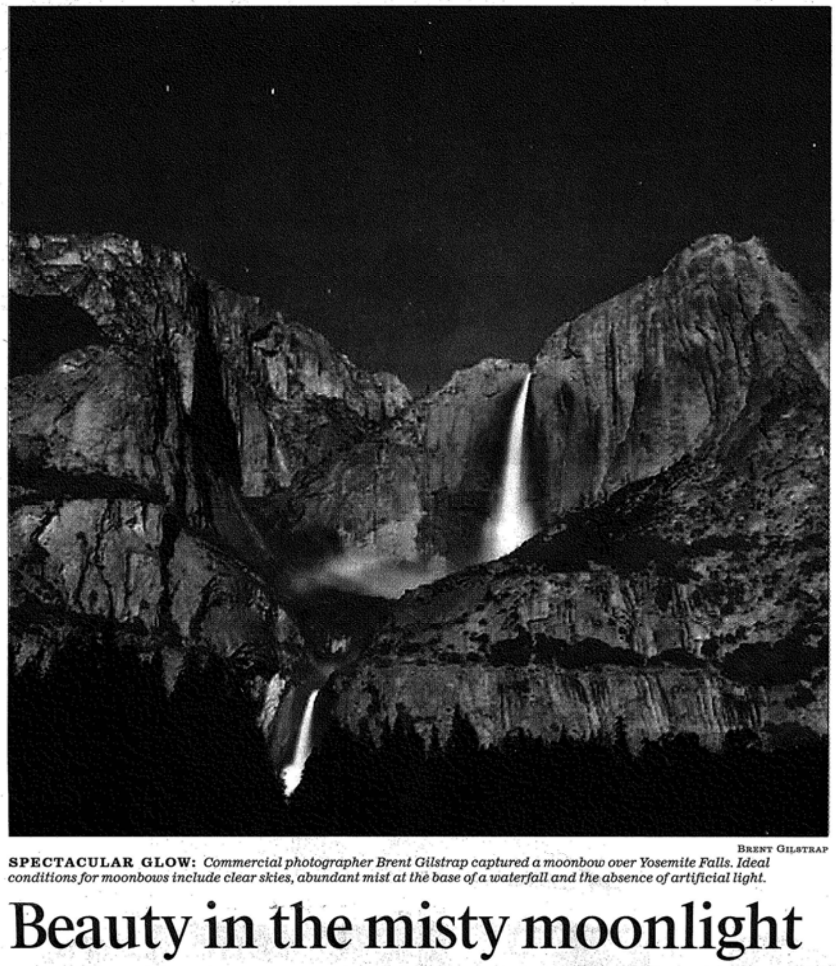
Hospitals, Page B8]



BRENT GILSTRAP

SPECTACULAR GLOW: *Commercial photographer Brent Gilstrap captured a moonbow over Yosemite Falls. Ideal conditions for moonbows include clear skies, abundant mist at the base of a waterfall and the absence of artificial light.*

Beauty in the misty moonlight

Elusive moonbows have long graced Yosemite Falls. Now a team of astronomers can predict when they will occur.

By ERIC BAILEY
Times Staff Writer

YOSEMITE NATIONAL PARK — Aristotle took note of this celestial happening a couple of millenniums back. Ben Franklin bagged a sighting or two, as did Mark Twain. The venerable John Muir, chronicler of Sierra mountaintop and meadow, waxed enthusiastic about the nighttime phenomenon.

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[*See Moonbow, Page B10*]

Mayor seeks to ease MTA hikes

Villaraigosa proposes smaller increases to help low-income bus riders and suggests ways the agency can free up cash to cover expected deficit.

By DUKE HELFAND AND STEVE HYMON
Times Staff Writers

Assailing sweeping bus fare hikes proposed by the MTA as "extreme," Los Angeles Mayor Antonio Villaraigosa on Monday called for more modest increases that would ease the financial crunch on low-income riders.

Villaraigosa offered his plan as part of a larger strategy to address the agency's estimated $104-million deficit for the coming fiscal year, a figure that Metropolitan Transportation Authority officials fear could balloon without new revenue. The MTA provides mass transit across Los Angeles County.

To make up for the more modest increases, the mayor suggested that the transit agency free up cash by borrowing money to finance the purchase of buses and rail cars over the coming years, slightly reduce the frequency of rail service and aggressively pursue state gas tax money.

Villaraigosa, who sits on the 13-member MTA board along with three of his appointees, laid out his scenario in a letter to fellow board members. The board is scheduled to vote on the fare hikes Thursday.

Under the mayor's plan, cash fares would remain untouched at $1.25. Other prices would rise about 5% annually to keep up with labor and fuel expenses.

As a result, the mayor proposed that the cost of a day pass would rise from its current level of $3 to $3.31 in 2009 — compared with MTA's proposal of a hike to $8 in that span.

Moonbows predictably wow fans

[*Moonbow, from Page B1*]
been dependably making spectacular shots of moonbows ever since he learned of the Texas State lunar table.

What may be his most remarkable moonbow photo came not at the fall's base but across the valley on a cloudless night last year. Gilstrap caught a broad panorama: the entire Yosemite Falls cascading down with a moonbow arching across mist halfway up the sheer cliff face, the whole scene reflected in mirrored waters of a flooded meadow.

On a recent and far less perfect night, the moon was dodging in and out of a gauzy bank of high clouds preceding a spring storm that hit the next day. By 10 p.m. the moonbow was a ghostly arch floating above the creek's granite rubble.

"Honestly, it was pretty lousy until a few minutes ago," Gilstrap yelled above the roar of the waterfall, his parka whipping in the rush of wind and mist coursing down the gorge.

At any one time during the course of the evening, a dozen people paused to take in the nighttime spectacle.

John Wolfarth, visiting from Boston, wasn't disappointed.

"Oh, there it is! There it is! There it is!" he yelled to his friend Kevin Powers. "That's amazing!"

Bruce Wang, a 28-year-old UC San Francisco medical student, had driven four hours from the Bay Area just to photograph the moonbow.

He arrived at 5 p.m., spent hours making moonbow shots with his tripod-mounted camera, then at 11 p.m. packed up to head home.

"Hopefully I'll be home by 2:30 a.m., get a few hours sleep and get to classes by 10 a.m.," he said. "I'm just lucky enough to live close enough to do this. It's a really cool natural phenomenon."

Olson said he had known about moonbows since his days in the graduate program at UC Berkeley and had long been mulling a project to create a table tracking their appearances.

The opportunity presented itself in 2005, when he and Texas State lecturer Russell Doescher arrived in the valley with a team of students.

With the water low, they could venture into the creek bed below Yosemite Falls to make the measurements needed to plot important factors for moonbow observations, including the true horizon of Yosemite Valley's southern cliffs, which can block a moonrise.

Back at the university, Olson, Doescher and students Kellie Beicker, Ashley Ralph and Hui-Yiing Chang from the school's Mitte Honors program crafted a computer model factoring in the various earthbound and celestial coordinates. They conducted real-world tests in 2006 that proved their calculations were spot on.

This year they went public, writing an article for May's Sky and Telescope magazine and posting on the university's website a schedule of moonbows anticipated in the mist of Lower Yosemite Fall.

A little luck is still needed. A good moonbow requires clear sky, abundant mist at the base of the fall, an absence of artificial light and what Olson calls the correct "rainbow geometry."

The predictions have sparked a sort of moonbow renaissance at the park. Well-known photographer Keith Walklet has conducted moonbow workshops and offers photo tips on the Ansel Adams Gallery website at *www.anseladams.com/content/newsletter/lunar_rainbow.html*.

The moonbow, also known as a lunar rainbow and moon rainbow, isn't unique to Yosemite Falls. Photographers have shot them arching in the mist of other waterfalls around the valley. In fact, Olson said, any big waterfall will suffice, provided it is roaring with spring snowmelt and correctly positioned to snag the moon's rays.

Moonbow tours are common at Africa's Victoria Falls. They're a ritual at Cumberland Falls in Kentucky, where early postcards show a hotel named the Moonbow Inn. Niagara Falls, Olson said, was known for spectacular moonbows before electricity put its rushing waters under a perpetual spotlight.

If you can't get to Yosemite or other moonbow hotbeds, Olson has a simple solution.

The next time a full moon rises in the night sky, grab a backyard garden hose and turn on the tap.

Keep the glowing lunar face to your back, and a fine mist sprayed skyward will produce an arch of luminescence, a homemade moonbow.

The schedule of moonbows can be found online at *uweb.txstate.edu/~do01*.

Gilstrap's moonbow photographs are online at *groundhog.smugmug.com/gallery/1036309/1/69899911/Original*.

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Appendix B

The predictions for 2006, 2007, 2008, and 2009 were displayed as the following tables on Dr. Olson's webpage, http://uweb.txstate.edu/~do01/. In addition to the predictions, the observing location and conditions required to observe a moonbow in the fall were given as follows.

Observing Location: Viewing area, terrace at the west end of the bridge near the base of Lower Yosemite Fall

Conditions required to observe a moonbow in Lower Yosemite Fall for observers at the viewing area, the terrace just west of the bridge near the base of Lower Yosemite Fall

1. bright moonlight (nearly-full Moon)
2. Moon risen above the south rim of the valley (so moonlight can strike Lower Yosemite Fall)
3. sufficient mist and spray (during snowmelt runoff season: April, May, June, sometimes July)
4. clear skies
5. dark skies (after nautical twilight has ended, so the Sun is more than 12 degrees below the horizon)
6. geometry (the angle between the "anti-lunar direction" [observer's shadow cast by the moonlight] and the direction toward the base of Lower Yosemite Fall must be near the "rainbow angle" of 42 degrees)

Note: If the snowmelt runoff is unusually strong then moonbows could appear earlier and last longer than predicted times. Conversely, if the snowmelt runoff is unusually weak, then moonbows would be visible for shorter intervals than the predicted times above.

MOONBOW PREDICTIONS FOR 2006
LOWER YOSEMITE FALL

DATE IN 2006	TIMES (PACIFIC DAYLIGHT TIME)	LUNAR PHASE	WHERE IS THE MOON? (FOR AN OBSERVER FACING LOWER YOSEMITE FALL)	WHERE IS THE TOP OF THE MOONBOW?	REMARKS
April 12 (Wed)	8:30pm (Wed) to 10:40pm (Wed)	100%	Moon above the ridge between Half Dome and Grizzly Peak (behind observer's right shoulder) at 8:30pm; above Glacier Point (directly behind observer) at 10:40pm	top of bow is to left of waterfall at 8:30pm; below base of waterfall at 10:40pm	moonbow already in progress when sky gets dark enough (at end of nautical twilight at 8:30pm)
night of April 13-14 (Thurs-Fri)	9:00pm (Thurs) to 12:05am (Fri)	100%	Moon above Grizzly Peak (behind observer's right shoulder) at 9:00pm; above Sentinel Dome (behind observer's left shoulder) at 12:05am	top of bow is above and to left of waterfall at 9:00pm, then passes through mist at 11:15pm, then below and to right of waterfall at 12:05am	moonbow grows brighter during evening as Moon rises higher; geometry produces a very long duration moonbow
night of April 14-15 (Fri-Sat)	11:35pm (Fri) to 1:20am (Sat)	97% waning	Moon above Glacier Point (directly behind observer) at 11:35pm; above Sentinel Dome (behind observer's left shoulder) at 1:00am	top of bow in waterfall near midnight, shifts to right of waterfall after midnight	
May 10 (Wed)	9:02pm (Wed) to 9:45pm (Wed)	96% waxing	Moon above south rim of valley between Glacier Point and Moran Point (directly behind observer)	top of bow near base of waterfall	moonbow already in progress when sky gets dark enough (at end of nautical twilight at 9:02pm)
May 11 (Thurs)	9:10pm (Thurs) to 11:00pm (Thurs)	99% waxing	Moon above Glacier Point (almost directly behind observer) at 9:10pm; above Sentinel Dome (behind observer's left shoulder) at 11:00pm	top of bow is above and to left of waterfall at 9:10pm, then passes through mist at 9:50pm, then is below and to right of waterfall at 11:00pm	
night of May 12-13 (Fri-Sat)	10:40pm (Fri) to 12:15am	100%	Moon above Moran Point (directly behind observer) at 10:40pm; above Sentinel Rock (behind	top of bow to right of waterfall	**brightest moonbow for 2006** (full Moon occurs at 11:51pm, during

	(Sat)		observer’s left shoulder) at 12:15am		moonbow)
night of May 13-14 (Sat-Sun)	11:55pm (Sat) to 1:25am (Sun)	99% waning	Moon above Sentinel Dome (behind observer’s left shoulder) at 11:55pm; above Sentinel Rock (behind observer’s left shoulder) at 1:25am	top of bow to right of waterfall	
night of May 14-15 (Sun-Mon)	1:19am (Mon) to 2:30am (Mon)	95% waning	Moon above Sentinel Dome (behind observer’s left shoulder) at 1:19am; above Sentinel Rock (behind observer’s left shoulder) at 2:30am	top of bow to right of waterfall	moonbow appears just as Moon clears south rim of valley near Sentinel Dome
June 9 (Fri)	9:40pm (Fri) to 11:10pm (Fri)	97% waxing	Moon above Moran Point (directly behind observer) at 9:40pm; above Sentinel Rock (behind observer’s left shoulder) at 11:10pm	top of bow to right of waterfall	moonbow appears just as Moon clears south rim of valley above Moran Point
night of June 10-11 (Sat-Sun)	10:59pm (Sat) to 12:20am (Sun)	100%	Moon above Sentinel Dome (behind observer’s left shoulder) at 10:59pm; above Sentinel Rock (behind observer’s left shoulder) at 12:20am	top of bow to right of waterfall	moonbow appears just as Moon clears south rim of valley near Sentinel Dome
night of June 11-12 (Sun-Mon)	12:09am (Mon) to 1:20am (Mon)	99% waning	Moon above Sentinel Dome (behind observer’s left shoulder) at 12:09am; near Sentinel Rock (behind observer’s left shoulder) at 1:20am	top of bow to right of waterfall	moonbow appears just as Moon clears south rim of valley near Sentinel Dome
night of June 12-13 (Mon-Tues)	1:06am (Tues) to 2:20am (Tues)	96% waning	Moon above Sentinel Dome (behind observer’s left shoulder) at 1:06am; near Sentinel Rock (behind observer’s left shoulder) at 2:20am	top of bow to right of waterfall	moonbow appears just as Moon clears south rim of valley near Sentinel Dome
July 9 (Sun)	11:00pm (Sun) to 11:40pm (Sun)	99% waxing	Moon near Sentinel Dome (behind observer’s left shoulder) at 11:00pm; near Sentinel Rock (behind observer’s left shoulder) at 11:40pm	top of bow to right of waterfall	depending on snow season and snowmelt runoff
night of July 10-11 (Mon-Tues)	11:55pm (Mon) to 12:35am	100%	Moon above Sentinel Dome (behind observer’s left shoulder) at 11:55pm; near Sentinel Rock (behind	top of bow to right of waterfall	brightest moonlight for July 2006; according to John Muir, moonbows

	(Tues)		observer’s left shoulder) at 12:35am		can be visible in July, depending on the snow season and snowmelt runoff.
night of July 11-12 (Tues-Wed)	12:35am (Wed) to 1:20am (Wed)	98% waning	Moon above Sentinel Dome (behind observer’s left shoulder)	top of bow to right of waterfall	depending on snow season and snowmelt runoff

MOONBOW PREDICTIONS FOR 2007
LOWER YOSEMITE FALL

DATE IN 2007	TIMES (PACIFIC DAYLIGHT TIME)	LUNAR PHASE	WHERE IS THE MOON? (FOR AN OBSERVER FACING LOWER YOSEMITE FALL)	WHERE IS THE TOP OF THE MOONBOW?	REMARKS
April 29 (Sun)	8:32pm (Sun) to 9:20pm (Sun)	96% waxing	Moon is above the ridge between Mount Starr King and Glacier Point (behind observer's right shoulder) at 8:32pm; above south rim of valley between Glacier Point and Moran Point (directly behind observer) at 9:20pm	top of bow is to left of waterfall at 8:32pm; below base of waterfall at 9:20pm	moonbow is already in progress when sky gets dark enough at about 8:32pm
April 30 (Mon)	8:33pm (Mon) to 10:40pm (Mon)	99% waxing	Moon above Mount Starr King (behind observer's right shoulder) at 8:33pm; above Sentinel Dome (behind observer's left shoulder) at 10:40pm	top of bow above and to left of waterfall at 8:33pm, then below and to right of waterfall at 10:40pm	moonbow is already in progress when sky gets dark enough at about 8:33pm
May 1 (Tues)	10:05pm (Tues) to 11:50pm (Tues)	100%	Moon above Glacier Point (almost directly behind observer) at 10:05pm; above the south rim of the valley between Sentinel Dome and Sentinel Rock (behind observer's left shoulder) at 11:50pm	top of bow above and to left of waterfall at 10:05pm, then below and to right of waterfall at 11:50pm	**brightest moonbow for 2007** (full Moon occurs at 3:09am PDT on May 2)
night of May 2-3 (Wed-Thurs)	11:25pm (Wed) to 1:00am (Thurs)	99% waning	Moon above Moran Point (almost directly behind observer) at 11:25pm; above Sentinel Rock (behind observer's left shoulder) at 1:00am	top of bow in waterfall at 11:25pm, then below and to right of waterfall at 1:00am	
night of May 3-4 (Thurs-Fri)	12:37am (Fri) to 2:00am (Fri)	96% waning	Moon above south rim of valley near Sentinel Dome (behind observer's left shoulder) at 12:37am; above Sentinel Rock (behind observer's left shoulder) at 2:00am	top of bow to right of waterfall	moonbow appears just as Moon clears south rim of valley near Sentinel Dome
May 29 (Tues)	9:10pm (Tues)	97% waxing	Moon above Moran Point (directly behind observer)	top of bow in waterfall at 9:10pm then shifts to	

	to 10:50pm (Tues)		at 9:10pm; near Sentinel Rock (behind observer's left shoulder) at 10:50pm	right of waterfall	
May 30 (Wed)	10:26pm (Wed) to 11:50pm (Wed)	99% waxing	Moon above south rim of valley between Moran Point and Sentinel Dome (behind observer's left shoulder) at 10:26pm; above Sentinel Rock (behind observer's left shoulder) at 11:50pm	top of bow to right of waterfall	moonbow appears just as Moon clears south rim of valley between Moran Point and Sentinel Dome
night of May 31- June 1 (Thurs-Fri)	11:33pm (Thurs) to 12:55am (Fri)	100%	Moon above Sentinel Dome (behind observer's left shoulder) at 11:33pm; above Sentinel Rock (behind observer's left shoulder) at 12:55am	top of bow to right of waterfall	moonbow appears just as Moon clears south rim of valley near Sentinel Dome
night of June 1-2 (Fri-Sat)	12:39am (Sat) to 1:50am (Sat)	98% waning	Moon above Sentinel Dome (behind observer's left shoulder) at 12:39am; above Sentinel Rock (behind observer's left shoulder) at 1:50am	top of bow to right of waterfall	moonbow appears just as Moon clears south rim of valley near Sentinel Dome
June 28 (Thurs)	10:35pm (Thurs) to 11:25pm (Thurs)	98% waxing	Moon above Sentinel Dome (behind observer's left shoulder) at 10:35pm; above Sentinel Rock (behind observer's left shoulder) at 11:25pm	top of bow to right of waterfall	depending on snow season and snowmelt runoff
night of June 29-30 (Fri-Sat)	11:30pm (Fri) to 12:20am (Sat)	100%	Moon above Sentinel Dome (behind observer's left shoulder) at 11:30pm; above Sentinel Rock (behind observer's left shoulder) at 12:20am	top of bow to right of waterfall	brightest moonlight for this lunar month; according to John Muir, moonbows can be visible in late June and July, depending on snow season and snowmelt runoff
night of June 30- July 1 (Sat-Sun)	12:20am (Sun) to 1:05am (Sun)	99% waning	Moon above Sentinel Dome (behind observer's left shoulder) at 12:20am; near Sentinel Rock (behind observer's left shoulder) at 1:05am	top of bow to right of waterfall	depending on snow season and snowmelt runoff
night of July 1-2 (Sun-Mon)	12:55am (Mon) to	96% waning	Moon above Sentinel Dome (behind observer's left shoulder) at 12:55am;	top of bow to right of waterfall	depending on snow season and snowmelt runoff

	1:45am (Mon)		above south rim of valley between Sentinel Dome and Sentinel Rock (behind observer's left shoulder) at 1:45am		

MOONBOW PREDICTIONS FOR 2008
LOWER YOSEMITE FALL

DATE IN 2008	TIMES (PACIFIC DAYLIGHT TIME)	LUNAR PHASE	REMARKS
April 18 (Fri)	8:21pm (Fri) to 10:15pm (Fri)	99% waxing	moonbow is already in progress when sky gets dark enough at about 8:21pm
April 19 (Sat)	8:22pm (Sat) to 11:30pm (Sat)	100%	**brightest moonbow for 2008** moonbow is already in progress when sky gets dark enough at about 8:22pm (full Moon occurs at 3:25am PDT on April 20)
night of April 20-21 (Sun-Mon)	11:00pm (Sun) to 12:40am (Mon)	99% waning	
night of April 21-22 (Mon-Tues)	12:17am (Tues) to 1:45am (Tues)	96% waning	moonbow appears just as Moon clears south rim of valley between Moran Point and Sentinel Dome
May 17 (Sat)	8:51pm (Sat) to 10:30pm (Sat)	97% waxing	moonbow is already in progress when sky gets dark enough at about 8:51pm
May 18 (Sun)	10:06pm (Sun) to 11:40pm (Sun)	99% waxing	moonbow appears just as Moon clears south rim of valley between Moran Point and Sentinel Dome
night of May 19-20 (Mon-Tues)	11:14pm (Mon) to 12:40am (Tues)	100%	**very bright moonbow** moonbow appears just as Moon clears south rim of valley near Sentinel Dome (full Moon occurs at 7:11pm PDT on May 19)
night of May 20-21 (Tues-Wed)	12:17am (Wed) to	98% waning	moonbow appears just as Moon clears south rim of valley near Sentinel Dome

	1:40am (Wed)		
night of May 21-22 (Wed-Thurs)	1:16am (Thurs) to 2:30am (Thurs)	95% waning	moonbow appears just as Moon clears south rim of valley near Sentinel Dome
June 16 (Mon)	10:13pm (Mon) to 11:25pm (Mon)	98% waxing	moonbow appears just as Moon clears south rim of valley near Sentinel Dome
night of June 17-18 (Tues-Wed)	11:12pm (Tues) to 12:20am (Wed)	100%	moonbow appears just as Moon clears south rim of valley near Sentinel Dome
night of June 18-19 (Wed-Thurs)	12:01am (Thurs) to 1:10am (Thurs)	99% waning	moonbow appears just as Moon clears south rim of valley near Sentinel Dome
night of June 19-20 (Thurs-Fri)	12:34am (Fri) to 1:55am (Fri)	97% waning	moonbow appears just as Moon clears south rim of valley near Sentinel Dome

MOONBOW PREDICTIONS FOR 2009
LOWER YOSEMITE FALL

DATE IN 2009	TIMES (PACIFIC DAYLIGHT TIME)	LUNAR PHASE	REMARKS
April 7 (Tues)	8:10pm (Tues) to 9:01pm (Tues)	98% waxing	moonbow is already in progress when sky gets dark enough at about 8:10pm
April 8 (Wed)	8:10pm (Wed) to 10:50pm (Wed)	100%	**brightest moonbow for 2009** moonbow is already in progress when sky gets dark enough at about 8:10pm (full Moon occurs at 7:56am PDT on April 9)
night of April 9-10 (Thurs-Fri)	10:00pm (Thurs) to 12:15am (Fri)	99% waning	depending on snowmelt runoff, moonbow may even be visible as early as 9:15pm on Thursday evening
night of April 10-11 (Fri-Sat)	11:50pm (Fri) to 1:25am (Sat)	97% waning	
May 6 (Wed)	8:40pm (Wed) to 10:00pm (Wed)	96% waxing	moonbow is already in progress when sky gets dark enough at about 8:40pm
May 7 (Thurs)	9:25pm (Thurs) to 11:15pm (Thurs)	99% waxing	
night of May 8-9 (Fri-Sat)	10:45pm (Fri) to 12:25am (Sat)	100%	(full Moon occurs at 9:01pm PDT on May 8)
night of May 9-10 (Sat-Sun)	12:01am (Sun) to 1:25am (Sun)	98% waning	moonbow appears just as Moon clears south rim of valley near Sentinel Dome

June 5 (Fri)	9:50pm (Fri) to 11:15pm (Fri)	98% waxing	moonbow appears just as Moon clears south rim of valley between Moran Point and Sentinel Dome
night of June 6-7 (Sat-Sun)	10:52pm (Sat) to 12:15am (Sun)	100%	moonbow appears just as Moon clears south rim of valley near Sentinel Dome (full Moon occurs at 11:12am PDT on June 7)
night of June 7-8 (Sun-Mon)	11:46pm (Sun) to 1:10am (Mon)	100%	moonbow appears just as Moon clears south rim of valley near Sentinel Dome
night of June 8-9 (Mon-Tues)	12:32am (Tues) to 1:50am (Tues)	98% waning	moonbow appears just as Moon clears south rim of valley near Sentinel Dome

Appendix C

As the heart and soul of this project, our program is the key to being able to make quick, reliable predictions for the occurrence of moonbows in Lower Yosemite Fall.
What follows is the code for our BASIC program, a sample input file (a text file usually in Notepad) for the night of June 22, 2005, and a sample output file for the same day.

MOONBOWS PROGRAM

```
REM     MOONBOW
        DEFDBL A-Z
        OPEN "C:\OUTPUT\MB62205.TXT" FOR OUTPUT AS #1
        OPEN "C:\INPUT\MON62205.TXT" FOR INPUT AS #2

        CLS : PI = 4# * ATN(1#): RD = PI / 180#

        AWFDEG = 325#: HWFDEG = 11.75#
        RADEG = 42.3#
        PHIDEG = 37.75#

        AWFRAD = AWFDEG * RD: HWFRAD = HWFDEG * RD
        PHIRAD = PHIDEG * RD

REM      AM=AZ(MOON)       HM=ALT(MOON)
REM     AAM=AZ(ANTIMOON)  HAM=ALT(ANTIMOON)
REM     AWF=AZ(WATERFALL) HWF=ALT(WATERFALL)
REM     RADEG=RAINBOW ANGLE   WDEG=RADIUS OF SPRAY
REM     PHI=LATITUDE OF YOSEMITE
REM     KMOON=ILLUMINATED FRACTION(MOON)
REM     IMOON=PHASE ANGLE (SUN-MOON-EARTH)

REM     PRINT HEADERS ON SCREEN AND ON FILE

        PRINT "                  MOON     MOON  MOON         ANTIMOON TOP OF BOW  BOW FROM  SLOPE"
        PRINT "TIME              K       DEC   ALT   AZ      ALT   AZ       ALT   MIST CTR ANGLE *** D(KM)
BRIGHTNESS"
```

```
        PRINT #1, "                    MOON     MOON  MOON          ANTIMOON TOP OF BOW  BOW FROM
SLOPE"
        PRINT #1, "TIME                K        DEC   ALT    AZ       ALT    AZ       ALT     MIST CTR ANGLE *** D(KM)
BRIGHTNESS"

REM     GET MOON DATA FROM JPL HORIZONS FILE

100     REM
REM     IF EOF(2) = -1 THEN CLOSE #2: CLOSE #1: END
        INPUT #2, PDT$, TWILIGHT$, MOONLIGHT$, RASCMDEG, DECMDEG, AMDEG, HMDEG, AIRMASS,
MVISMOON, SBMOON, KMOON, RSUNAU, RSUNDOT, DELTAAU, DELTADOT, IMOON, CONST$
        IF PDT$ = "999" THEN GOTO 999

        DECMRAD = DECMDEG * RD
        AMRAD = AMDEG * RD: HMRAD = HMDEG * RD

REM     CALCULATE COORDINATES OF ANTIMOON
        HAMDEG = -HMDEG: HAMRAD = -HMRAD
        AAMDEG = AMDEG + 180#: AAMRAD = AMRAD + PI

REM     CALCULATE ANGULAR SEPARATION BETWEEN ANTIMOON AND WF
        T1 = COS(HWFRAD) * COS(HAMRAD) * COS(AWFRAD - AAMRAD)
        T2 = SIN(HWFRAD) * SIN(HAMRAD)
        CD = T1 + T2
        SD = SQR(1# - CD * CD)
        DRAD = ATN(SD / CD)
        IF CD < 0 THEN DRAD = DRAD + PI
        DDEG = DRAD / RD
        SUCCESS$ = " ***"
```

```
    IF DDEG < (RADEG - 8#) THEN SUCCESS$ = "    "
    IF DDEG > (RADEG + 5#) THEN SUCCESS$ = "    "
    IF TWILIGHT$ = "*" THEN SUCCESS$ = "    "
    IF TWILIGHT$ = "C" THEN SUCCESS$ = "    "
    IF TWILIGHT$ = "N" THEN SUCCESS$ = "    "

REM     CALCULATE TILT ANGLE
    T1 = SIN(AWFRAD - AAMRAD) / COS(HWFRAD)
    T2 = TAN(HAMRAD) - TAN(HWFRAD) * COS(AWFRAD - AAMRAD)
    TALPHA = T1 / T2
    ALPHARAD = ATN(TALPHA)
    ALPHADEG = ALPHARAD / RD

    IF (DDEG - RADEG) > 0 AND ALPHADEG > 0 THEN LOC$ = " LR"
    IF (DDEG - RADEG) > 0 AND ALPHADEG < 0 THEN LOC$ = " LL"
    IF (DDEG - RADEG) < 0 AND ALPHADEG > 0 THEN LOC$ = " UL"
    IF (DDEG - RADEG) < 0 AND ALPHADEG < 0 THEN LOC$ = " UR"

REM     CALCULATE BRIGHTNESS OF MOONLIGHT
REM     LUNAR PHASE LAW & OPPOSITION EFFECT  IMOON=PHASE ANGLE IN DEG
    DELTAMAG = .026# * ABS(IMOON) + (.000000004#) * ((ABS(IMOON)) ^ 4)
    F1 = 10# ^ (-.4 * DELTAMAG)
    IF ABS(IMOON) < 7 THEN F1 = F1 * (1.35 - .05 * ABS(IMOON))

REM     ATMOSPHERIC EXTINCTION
    F2 = 10# ^ (-.4 * .2 * (AIRMASS - 2.356))

REM     LUNAR DISTANCE
    DISTMOONKM = DELTAAU * 149597870.7#
```

```
    F3 = (385001# / DISTMOONKM) ^ 2

REM     SOLAR DISTANCE
    F4 = (1.01# / RSUNAU) ^ 2

REM     TOTAL
    FTOTAL = F1 * F2 * F3 * F4

    PRINT PDT$;
    PRINT TWILIGHT$;
    IF TWILIGHT$ = "" THEN PRINT " ";
    PRINT USING "###.###"; KMOON;
    PRINT USING "####.##"; DECMDEG;
    PRINT USING "###.##"; HMDEG;
    PRINT USING "####.##"; AMDEG;
    PRINT USING "####.##"; HAMDEG;
    PRINT USING "####.##"; AAMDEG;
    PRINT USING "####.##"; (RADEG - HMDEG);
    PRINT USING "###.##"; (RADEG - DDEG);
    PRINT LOC$;
    PRINT USING "####.##"; ALPHADEG;
    PRINT SUCCESS$;
    PRINT USING "#######"; DISTMOONKM;
    PRINT USING "##.###"; FTOTAL


    REM IF SUCCESS$ = "     " THEN GOTO 100
    REM DO NOT PRINT FAILURE TO FILE
```

```
    PRINT #1, PDT$;
    PRINT #1, TWILIGHT$;
    IF TWILIGHT$ = "" THEN PRINT #1, " ";
    PRINT #1, USING "###.###"; KMOON;
    PRINT #1, USING "####.##"; DECMDEG;
    PRINT #1, USING "###.##"; HMDEG;
    PRINT #1, USING "####.##"; AMDEG;
    PRINT #1, USING "####.##"; HAMDEG;
    PRINT #1, USING "####.##"; AAMDEG;
    PRINT #1, USING "####.##"; (RADEG - HMDEG);
    PRINT #1, USING "###.##"; (RADEG - DDEG);
    PRINT #1, LOC$;
    PRINT #1, USING "####.##"; ALPHADEG;
    PRINT #1, SUCCESS$;
    PRINT #1, USING "#######"; DISTMOONKM;
    PRINT #1, USING "##.###"; FTOTAL


    GOTO 100
    REM GET MORE DATA

999   CLOSE #1: CLOSE #2

    END
```

SAMPLE INPUT: MON62205.txt

2005-Jun-23 00:15, ,m,290.47683,-28.06113, 152.4820, 18.5232, 3.121, -12.39, 3.83, 97.774, 1.018668317245, -0.1884351, .002390450503385, -0.1599109, 17.1599, Sgr

2005-Jun-23 00:16, ,m,290.48543,-28.06067, 152.6871, 18.6117, 3.107, -12.39, 3.83, 97.773, 1.018668242868, -0.1885927, .002390386569859, -0.1587630, 17.1663, Sgr

2005-Jun-23 00:17, ,m,290.49402,-28.06020, 152.8926, 18.6997, 3.094, -12.39, 3.83, 97.771, 1.018668168428, -0.1887503, .002390323097308, -0.1576123, 17.1728, Sgr

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SAMPLE OUTPUT: MB62205.txt

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TIME               K      DEC    ALT    AZ       ALT    AZ      ALT    MIST CTR ANGLE *** D(KM)  BRIGHTNESS
2005-Jun-23 00:24  97.759 -28.06 19.30 154.34 -19.30 334.34  23.00  9.92 UL  16.62     357523 0.670
2005-Jun-23 00:25  97.758 -28.06 19.38 154.55 -19.38 334.55  22.92  9.78 UL  16.93     357514 0.671
2005-Jun-23 00:26  97.756 -28.06 19.46 154.76 -19.46 334.76  22.84  9.64 UL  17.23     357505 0.673
2005-Jun-23 00:27  97.754 -28.06 19.55 154.97 -19.55 334.97  22.75  9.50 UL  17.53     357496 0.674
2005-Jun-23 00:28  97.753 -28.05 19.63 155.18 -19.63 335.18  22.67  9.36 UL  17.83     357487 0.675
2005-Jun-23 00:29  97.751 -28.05 19.71 155.39 -19.71 335.39  22.59  9.22 UL  18.12     357479 0.677
2005-Jun-23 00:30  97.750 -28.05 19.79 155.60 -19.79 335.60  22.51  9.08 UL  18.42     357470 0.678
2005-Jun-23 00:31  97.748 -28.05 19.87 155.81 -19.87 335.81  22.43  8.94 UL  18.71     357462 0.679
2005-Jun-23 00:32  97.746 -28.05 19.95 156.02 -19.95 336.02  22.35  8.80 UL  19.00     357453 0.681
2005-Jun-23 00:33  97.745 -28.05 20.02 156.23 -20.02 336.23  22.28  8.66 UL  19.29     357445 0.682
2005-Jun-23 00:34  97.743 -28.05 20.10 156.45 -20.10 336.45  22.20  8.52 UL  19.58     357437 0.683
2005-Jun-23 00:35  97.741 -28.05 20.18 156.66 -20.18 336.66  22.12  8.37 UL  19.87     357428 0.684
2005-Jun-23 00:36  97.740 -28.05 20.25 156.87 -20.25 336.87  22.05  8.23 UL  20.15     357420 0.686
2005-Jun-23 00:37  97.738 -28.05 20.33 157.09 -20.33 337.09  21.97  8.09 UL  20.44     357412 0.687
2005-Jun-23 00:38  97.737 -28.05 20.40 157.30 -20.40 337.30  21.90  7.94 UL  20.72 *** 357404 0.688
2005-Jun-23 00:39  97.735 -28.05 20.48 157.51 -20.48 337.51  21.82  7.80 UL  21.00 *** 357396 0.689
2005-Jun-23 00:40  97.733 -28.05 20.55 157.73 -20.55 337.73  21.75  7.66 UL  21.28 *** 357388 0.690
2005-Jun-23 00:41  97.732 -28.05 20.63 157.94 -20.63 337.94  21.67  7.51 UL  21.56 *** 357380 0.692
2005-Jun-23 00:42  97.730 -28.05 20.70 158.16 -20.70 338.16  21.60  7.37 UL  21.83 *** 357373 0.693
2005-Jun-23 00:43  97.728 -28.04 20.77 158.37 -20.77 338.37  21.53  7.22 UL  22.11 *** 357365 0.694
2005-Jun-23 00:44  97.727 -28.04 20.84 158.59 -20.84 338.59  21.46  7.08 UL  22.38 *** 357358 0.695
2005-Jun-23 00:45  97.725 -28.04 20.91 158.80 -20.91 338.80  21.39  6.93 UL  22.65 *** 357350 0.696
2005-Jun-23 00:46  97.724 -28.04 20.98 159.02 -20.98 339.02  21.32  6.79 UL  22.92 *** 357343 0.697
2005-Jun-23 00:47  97.722 -28.04 21.05 159.24 -21.05 339.24  21.25  6.64 UL  23.19 *** 357335 0.698
2005-Jun-23 00:48  97.720 -28.04 21.12 159.46 -21.12 339.46  21.18  6.49 UL  23.46 *** 357328 0.699
2005-Jun-23 00:49  97.719 -28.04 21.19 159.67 -21.19 339.67  21.11  6.35 UL  23.72 *** 357321 0.700
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2005-Jun-23 00:50	97.717	-28.04	21.25	159.89	-21.25	339.89	21.05	6.20	UL	23.99	***	357314	0.701
2005-Jun-23 00:51	97.716	-28.04	21.32	160.11	-21.32	340.11	20.98	6.05	UL	24.25	***	357307	0.702
2005-Jun-23 00:52	97.714	-28.04	21.38	160.33	-21.38	340.33	20.92	5.91	UL	24.51	***	357300	0.703
2005-Jun-23 00:53	97.712	-28.04	21.45	160.55	-21.45	340.55	20.85	5.76	UL	24.77	***	357293	0.704
2005-Jun-23 00:54	97.711	-28.04	21.51	160.77	-21.51	340.77	20.79	5.61	UL	25.03	***	357286	0.705
2005-Jun-23 00:55	97.709	-28.04	21.58	160.99	-21.58	340.99	20.72	5.46	UL	25.29	***	357279	0.706
2005-Jun-23 00:56	97.708	-28.03	21.64	161.21	-21.64	341.21	20.66	5.31	UL	25.54	***	357272	0.706
2005-Jun-23 00:57	97.706	-28.03	21.70	161.43	-21.70	341.43	20.60	5.17	UL	25.80	***	357266	0.707
2005-Jun-23 00:58	97.704	-28.03	21.76	161.65	-21.76	341.65	20.54	5.02	UL	26.05	***	357259	0.708
2005-Jun-23 00:59	97.703	-28.03	21.82	161.87	-21.82	341.87	20.48	4.87	UL	26.31	***	357253	0.709
2005-Jun-23 01:00	97.701	-28.03	21.88	162.09	-21.88	342.09	20.42	4.72	UL	26.56	***	357246	0.710
2005-Jun-23 01:01	97.699	-28.03	21.94	162.31	-21.94	342.31	20.36	4.57	UL	26.81	***	357240	0.711
2005-Jun-23 01:02	97.698	-28.03	22.00	162.53	-22.00	342.53	20.30	4.42	UL	27.06	***	357234	0.711
2005-Jun-23 01:03	97.696	-28.03	22.06	162.76	-22.06	342.76	20.24	4.27	UL	27.31	***	357228	0.712
2005-Jun-23 01:04	97.695	-28.03	22.12	162.98	-22.12	342.98	20.18	4.12	UL	27.55	***	357222	0.713
2005-Jun-23 01:05	97.693	-28.03	22.17	163.20	-22.17	343.20	20.13	3.97	UL	27.80	***	357216	0.714
2005-Jun-23 01:06	97.692	-28.03	22.23	163.42	-22.23	343.42	20.07	3.82	UL	28.04	***	357210	0.714
2005-Jun-23 01:07	97.690	-28.03	22.29	163.65	-22.29	343.65	20.01	3.66	UL	28.28	***	357204	0.715
2005-Jun-23 01:08	97.688	-28.02	22.34	163.87	-22.34	343.87	19.96	3.51	UL	28.53	***	357198	0.716
2005-Jun-23 01:09	97.687	-28.02	22.39	164.10	-22.39	344.10	19.91	3.36	UL	28.77	***	357192	0.717
2005-Jun-23 01:10	97.685	-28.02	22.45	164.32	-22.45	344.32	19.85	3.21	UL	29.01	***	357187	0.717
2005-Jun-23 01:11	97.684	-28.02	22.50	164.54	-22.50	344.54	19.80	3.06	UL	29.25	***	357181	0.718
2005-Jun-23 01:12	97.682	-28.02	22.55	164.77	-22.55	344.77	19.75	2.91	UL	29.48	***	357176	0.719
2005-Jun-23 01:13	97.680	-28.02	22.60	164.99	-22.60	344.99	19.70	2.75	UL	29.72	***	357170	0.719
2005-Jun-23 01:14	97.679	-28.02	22.65	165.22	-22.65	345.22	19.65	2.60	UL	29.96	***	357165	0.720
2005-Jun-23 01:15	97.677	-28.02	22.70	165.45	-22.70	345.45	19.60	2.45	UL	30.19	***	357160	0.720
2005-Jun-23 01:16	97.676	-28.02	22.75	165.67	-22.75	345.67	19.55	2.29	UL	30.43	***	357154	0.721
2005-Jun-23 01:17	97.674	-28.02	22.80	165.90	-22.80	345.90	19.50	2.14	UL	30.66	***	357149	0.722
2005-Jun-23 01:18	97.672	-28.01	22.85	166.12	-22.85	346.12	19.45	1.99	UL	30.89	***	357144	0.722

2005-Jun-23 01:19	97.671	-28.01	22.89	166.35	-22.89	346.35	19.41	1.84	UL	31.12	***	357139	0.723
2005-Jun-23 01:20	97.669	-28.01	22.94	166.58	-22.94	346.58	19.36	1.68	UL	31.35	***	357135	0.723
2005-Jun-23 01:21	97.668	-28.01	22.98	166.81	-22.98	346.81	19.32	1.53	UL	31.58	***	357130	0.724
2005-Jun-23 01:22	97.666	-28.01	23.03	167.03	-23.03	347.03	19.27	1.37	UL	31.81	***	357125	0.724
2005-Jun-23 01:23	97.665	-28.01	23.07	167.26	-23.07	347.26	19.23	1.22	UL	32.03	***	357120	0.725
2005-Jun-23 01:24	97.663	-28.01	23.12	167.49	-23.12	347.49	19.18	1.07	UL	32.26	***	357116	0.725
2005-Jun-23 01:25	97.661	-28.01	23.16	167.72	-23.16	347.72	19.14	0.91	UL	32.48	***	357111	0.726
2005-Jun-23 01:26	97.660	-28.01	23.20	167.95	-23.20	347.95	19.10	0.76	UL	32.71	***	357107	0.726
2005-Jun-23 01:27	97.658	-28.01	23.24	168.18	-23.24	348.18	19.06	0.60	UL	32.93	***	357103	0.727
2005-Jun-23 01:28	97.657	-28.00	23.28	168.40	-23.28	348.40	19.02	0.45	UL	33.15	***	357098	0.727
2005-Jun-23 01:29	97.655	-28.00	23.32	168.63	-23.32	348.63	18.98	0.29	UL	33.37	***	357094	0.728
2005-Jun-23 01:30	97.653	-28.00	23.36	168.86	-23.36	348.86	18.94	0.14	UL	33.59	***	357090	0.728
2005-Jun-23 01:31	97.652	-28.00	23.40	169.09	-23.40	349.09	18.90	-0.02	LR	33.81	***	357086	0.729
2005-Jun-23 01:32	97.650	-28.00	23.43	169.32	-23.43	349.32	18.87	-0.17	LR	34.03	***	357082	0.729
2005-Jun-23 01:33	97.649	-28.00	23.47	169.55	-23.47	349.55	18.83	-0.33	LR	34.25	***	357078	0.729
2005-Jun-23 01:34	97.647	-28.00	23.50	169.78	-23.50	349.78	18.80	-0.48	LR	34.47	***	357074	0.730
2005-Jun-23 01:35	97.646	-28.00	23.54	170.01	-23.54	350.01	18.76	-0.64	LR	34.68	***	357071	0.730
2005-Jun-23 01:36	97.644	-27.99	23.57	170.25	-23.57	350.25	18.73	-0.80	LR	34.90	***	357067	0.731
2005-Jun-23 01:37	97.642	-27.99	23.61	170.48	-23.61	350.48	18.69	-0.95	LR	35.11	***	357064	0.731
2005-Jun-23 01:38	97.641	-27.99	23.64	170.71	-23.64	350.71	18.66	-1.11	LR	35.33	***	357060	0.731
2005-Jun-23 01:39	97.639	-27.99	23.67	170.94	-23.67	350.94	18.63	-1.27	LR	35.54	***	357057	0.731
2005-Jun-23 01:40	97.638	-27.99	23.70	171.17	-23.70	351.17	18.60	-1.42	LR	35.75	***	357053	0.732
2005-Jun-23 01:41	97.636	-27.99	23.73	171.40	-23.73	351.40	18.57	-1.58	LR	35.96	***	357050	0.732
2005-Jun-23 01:42	97.635	-27.99	23.76	171.63	-23.76	351.63	18.54	-1.73	LR	36.18	***	357047	0.732
2005-Jun-23 01:43	97.633	-27.99	23.79	171.87	-23.79	351.87	18.51	-1.89	LR	36.39	***	357044	0.733
2005-Jun-23 01:44	97.631	-27.99	23.82	172.10	-23.82	352.10	18.48	-2.05	LR	36.59	***	357041	0.733
2005-Jun-23 01:45	97.630	-27.98	23.85	172.33	-23.85	352.33	18.45	-2.20	LR	36.80	***	357038	0.733
2005-Jun-23 01:46	97.628	-27.98	23.87	172.56	-23.87	352.56	18.43	-2.36	LR	37.01	***	357035	0.734
2005-Jun-23 01:47	97.627	-27.98	23.90	172.80	-23.90	352.80	18.40	-2.52	LR	37.22	***	357032	0.734

2005-Jun-23	01:48	97.625	-27.98	23.92	173.03	-23.92	353.03	18.38	-2.68	LR	37.42	***	357030	0.734
2005-Jun-23	01:49	97.624	-27.98	23.95	173.26	-23.95	353.26	18.35	-2.83	LR	37.63	***	357027	0.734
2005-Jun-23	01:50	97.622	-27.98	23.97	173.49	-23.97	353.49	18.33	-2.99	LR	37.84	***	357025	0.734
2005-Jun-23	01:51	97.620	-27.98	23.99	173.73	-23.99	353.73	18.31	-3.15	LR	38.04	***	357022	0.735
2005-Jun-23	01:52	97.619	-27.98	24.01	173.96	-24.01	353.96	18.29	-3.31	LR	38.24	***	357020	0.735
2005-Jun-23	01:53	97.617	-27.97	24.04	174.19	-24.04	354.19	18.26	-3.46	LR	38.45	***	357018	0.735
2005-Jun-23	01:54	97.616	-27.97	24.06	174.43	-24.06	354.43	18.24	-3.62	LR	38.65	***	357015	0.735
2005-Jun-23	01:55	97.614	-27.97	24.08	174.66	-24.08	354.66	18.22	-3.78	LR	38.85	***	357013	0.735
2005-Jun-23	01:56	97.613	-27.97	24.09	174.90	-24.09	354.90	18.21	-3.94	LR	39.05	***	357011	0.735
2005-Jun-23	01:57	97.611	-27.97	24.11	175.13	-24.11	355.13	18.19	-4.09	LR	39.25	***	357009	0.736
2005-Jun-23	01:58	97.609	-27.97	24.13	175.36	-24.13	355.36	18.17	-4.25	LR	39.45	***	357007	0.736
2005-Jun-23	01:59	97.608	-27.97	24.15	175.60	-24.15	355.60	18.15	-4.41	LR	39.65	***	357006	0.736
2005-Jun-23	02:00	97.606	-27.96	24.16	175.83	-24.16	355.83	18.14	-4.57	LR	39.85	***	357004	0.736
2005-Jun-23	02:01	97.605	-27.96	24.18	176.07	-24.18	356.07	18.12	-4.73	LR	40.05	***	357002	0.736
2005-Jun-23	02:02	97.603	-27.96	24.19	176.30	-24.19	356.30	18.11	-4.89	LR	40.25	***	357001	0.736
2005-Jun-23	02:03	97.602	-27.96	24.20	176.54	-24.20	356.54	18.10	-5.04	LR	40.44		356999	0.736
2005-Jun-23	02:04	97.600	-27.96	24.22	176.77	-24.22	356.77	18.08	-5.20	LR	40.64		356998	0.736
2005-Jun-23	02:05	97.599	-27.96	24.23	177.01	-24.23	357.01	18.07	-5.36	LR	40.83		356996	0.736
2005-Jun-23	02:06	97.597	-27.96	24.24	177.24	-24.24	357.24	18.06	-5.52	LR	41.03		356995	0.736
2005-Jun-23	02:07	97.595	-27.95	24.25	177.48	-24.25	357.48	18.05	-5.68	LR	41.22		356994	0.736
2005-Jun-23	02:08	97.594	-27.95	24.26	177.71	-24.26	357.71	18.04	-5.84	LR	41.42		356993	0.736
2005-Jun-23	02:09	97.592	-27.95	24.27	177.95	-24.27	357.95	18.03	-5.99	LR	41.61		356992	0.736
2005-Jun-23	02:10	97.591	-27.95	24.28	178.18	-24.28	358.18	18.02	-6.15	LR	41.80		356991	0.736
2005-Jun-23	02:11	97.589	-27.95	24.28	178.42	-24.28	358.42	18.02	-6.31	LR	42.00		356990	0.736