

Quantification of Distant Luminous Objects

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Abstract With the advent of modern CCD cameras, it is possible to quantitate the total photon count of distant Luminous Objects. In this paper, I have developed a formula for astronomers to allow use of this fact to calculate the total photon output, and thus total energy output, of imaged objects. I then use SN 2002ap in M74 (NGC 628) as an example and calculate the total energy flux of that event.

1. Discussion

During the quiet time of image acquisition, my mind frequently wanders to the depths of space to contemplate the enormity of the event that is unfolding before me. The M74 supernova event in January/February 2002 (Nakano 2002) was one such contemplative time. As the CCD was absorbing photons for an image, and I watched through a smaller piggyback telescope, I wondered about the enormous amount of energy that I was witnessing.

At that moment it occurred to me that with the linear response of CCD cameras, it should be possible in principle to be able to quantify the energy output of the supernova by counting the total photons collected as a sample of the total energy output of the supernova.

To arrive at a calculation of the total energy output I have compiled all of the factors that would influence the total photon count and derived a formula that can be used by amateurs with CCD equipment:

$$\text{Total Flux} = \frac{(\text{gain}) (\sum I_{\text{pixel}_{1-N}}) (\text{AirM}) (\text{AreaSphere})}{(\text{QE}) (\text{TelMa}) (\text{Time}) (\text{MirReflec}) (\text{FilterFactor})}$$

The *gain* refers to the analog to digital conversion (ADC). This term can be obtained from the manufacturer of the CCD camera, or can be derived. To determine it, I refer the reader to the book *Astronomical Image Processing* (Berry and Burnell 2000, p. 193). This term gives the conversion of photons/electrons collected to ADU (Analog to Digital Units). For my Apogee AM13, which incorporates a Kodak 1300 chip, my ADC gain is 2.5. This means that for every 2.5 photons collected and recorded, I have intensity of 1 ADU. As long as the pixels are not saturated, this measurement is a linear one.

$\sum I_{\text{pixel}_{1-N}}$ is the total ADU intensity count of the supernova on the image, and is a number calculated per pixel. The image of the supernova is smeared over many pixels in a gaussian distribution. Each pixel has an intensity ADU count associated with it. From this count must be subtracted the dark current bias, and any background

photons such as sky glow and the spiral arm that the supernova is superimposed on. Then, one integrates that total count for each pixel that contributes to the image of the star.

This can be done by enlarging the image and counting the intensity of each pixel radially outwards until it matches the background. Software can also do this time-consuming task, such as single star photometry in *AIP4WIN* (Berry 2000), or it can be done manually. I performed this calculation both manually and by software with essentially no difference between the two, validating the accuracy of the software. If done manually you should average about 20 pixels around the immediate area of the supernova and subtract that from every supernova pixel element. Using software, choose an annulus for the star large enough to completely count all pixels of the star, even those in the tail ends of the gaussian curve, then use an annulus that encircles this smaller annulus to subtract out the galactic arm.

AirM, air mass, or degree of atmospheric extinction, refers to the absorption and scatter of photons by our atmosphere. At the zenith near sea level on a calm clear night, the air causes a 0.24 magnitude loss, or a 49% loss of photons, as extinction is a log function. 30 degrees up from the horizon results in two air masses, that is, twice as much atmosphere is traversed by the light path, causing a 0.48 mag loss, or a 63% loss of photons. 15 degrees from the horizon is 3 atmospheres (0.72 mag), and 10 degrees from the horizon is 4 atmospheres or 0.96 mag (~ 1 complete magnitude) lost, which is a loss of 2.5 photons for every one that gets through (72% loss). Note that there is a differential absorption and scatter for various wavelengths, with greater loss for blue than red (Berry and Burnell 2000, pp. 248, 475).

AreaSphere of energy refers to an expanding sphere or pulse of energy from the event recorded (Figure 1). This is, of course, the single most important factor that sets the scale of the event, with all other factors mentioned merely modifiers of the scale of the event. This is because of the enormous distance involved, that to give any significant photon count implies a greater energy with greater distance involved. The photon count collected through the capture of the telescope is a miniscule fraction of the total count of an enormous sphere, assuming that the object radiates in all directions equally and simultaneously, or is isotropically radiating. The area of the sphere is $4\pi r^2$, and the r is a very large number. As the distance to M74 is reported to be 34 million (3.4×10^7) light-years, the distance in meters to M74 is 3.23×10^{23} .

QE refers to the quantum efficiency of the chip. This varies widely for various CCD cameras and you need to know or calculate this. This number varies by the efficiency of capture of photons, with one photon generating an electron. This percentage of efficiency would include photons not captured, and also those that fall on read out channels and not registered or absorbed. This efficiency rating varies over the spectrum to which the chip is sensitive. For complete accuracy an image should be obtained with a set of known filters, than summed together. My camera has an overall QE of 40%, with the blue significantly weaker than the red.

TelMa is the telescope mirror surface area, defined by πr^2 . The total mirror area

of the telescope is calculated to normalize the photon flux to meter squared on earth. For my 32-inch (0.8 meter) telescope this becomes $\pi 0.4^2$ or 0.54m^2 . The inverse of this becomes the photon flux/ m^2 .

Time simply refers to the integration time. Set whatever time standard you wish to record. I choose to determine the photon count/second and thus divide by the integration time in seconds. The integration time of the image, of course, must be in the linear range of the CCD chip and not saturated.

MirReflec represents telescope mirror reflectivity. Assuming a clean mirror, the reflectance of a good surface is 92%. A two-mirror surface would be 0.92^2 or 84% for a typical Newtonian telescope. Refractors vary widely, depending on coatings, but typical is 96% transmittance for a good multicoated refractor.

For *FilterFactor* I used an average quantum efficiency in this exercise as the image was unfiltered. For true accuracy and to help determine the black body radiation curve, measurements in *BVRI* should be done, but then you must know and correct for the transmittance of each filter used.

Interstellar absorption is an unknown, but this is not a significant problem and merely would increase the final number, thus the answer can be considered the lower limit.

Once the number is determined, a representation of the total photon flux in visible and near infrared is obtained. While this is a remarkable fact for simple amateur equipment, it is possible to extend this further. Most luminous events such as supernovae emit as black body radiation, with emission objects being the notable exception. Black body radiation has a characteristic curve, with the peak determined by the temperature of the luminous object. Thus, if several careful measurements are taken in blue, visual, and infrared, then the total intensity of each can be graphed and the slope of the blackbody curve can be estimated. From that, the area under the curve can be integrated, and the total energy flux in photons has now been obtained. As supernovae give half of the total energy as neutrinos, double the final answer for the total energy output. Note that a photon of visible light has an energy of about two electron volts, which can be converted to ergs and then to any convenient energy unit for total energy output. Once the telescope/CCD system is calibrated, this formula can be used for any type of luminous object desired, such as variable stars.

2. Example

As an example I present SN 2002ap, the supernova in M74 (NGC 628) from January 2002. Comparing a prior year photo (Figure 2) with the image of M74 showing the supernova (Figure 3), it is clearly seen that the supernova occurs in an outer spiral arm. If we expand the image to view the individual pixels and measure the ADU of each pixel involved in the image of the supernova, we can obtain the total ADU count of the supernova, as long as the surrounding value of the spiral arm is subtracted from every pixel. The ADU count obtained in this case is 850403. This number is multiplied by the gain of 2.5 for a result of 2.13×10^6 . The AirM is 2.14.

The area of the sphere of energy ($4\pi r^2$)

$$4 \times 3.14 \times (3.23 \times 10^{23})^2 = 1.3 \times 10^{47} \text{ m}^2,$$

is an enormous number; this clearly gives the scale of the event.

The top half of the flux equation becomes

$$(8.5 \times 10^5) (2.5) (2.14) (1.3 \times 10^{47}) = 5.91 \times 10^{53}.$$

The QE of my Apogee unfiltered camera averaged over all wavelengths is 40%, taking into account nonabsorption and insensitive areas. TelMa for my 32-inch scope (0.8m) is $\pi r^2 = 0.54 \text{ m}^2$. The integration time was 180 seconds, chosen to prevent saturation. I in fact took 5 separate images and median-combined them to improve signal-to-noise, but the integration time remains the same. Mirror reflection for my two-mirror Newtonian is 0.84. Finally, no filters were used in this example, primarily due to bad weather and a setting galaxy observed shortly after sunset, limiting my time. The bottom half of the flux equation becomes

$$(0.40) (0.54) (180) = 32.66.$$

Thus, the final tally is $5.85 \times 10^{53} / 32.66 = 1.8 \times 10^{52}$ photons/second in visible/IR light.

To convert this to standard solar output, first convert to ergs: one photon = 2 e.v., or 3.2×10^{-12} ergs/sec. Converting, the supernova had an output of 5.76×10^{40} ergs/sec. Since the solar output is 3.85×10^{33} ergs/sec, the supernova can be converted to 1.5×10^7 sols/sec (conversion data provided courtesy Dr. Matthew Templeton, AAVSO Headquarters).

One could integrate the total energy of the event as mentioned earlier by calculating the blackbody curve and converting photons to e.v. energy units. One could take multiple measurements over a one to two month period and determine the total energy of the event, all with fairly simple amateur equipment. The CCD is a marvelous and revolutionary tool with untapped potential for future research and discoveries.

References

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 Berry, R., Burnell, J. 2000, *Astronomical Image Processing*, pp. 193, 248, 475, Willman-Bell, Inc., Richmond, VA.
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 Templeton, M. 2002, private communication.

SPHERE =
Sphere of expanding energy

light year = (300,000 k/s)
(31,536,000 sec/year) =
 9.5×10^{12} km

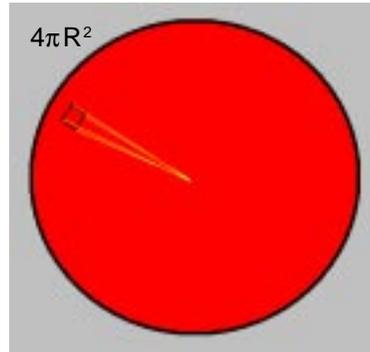


Figure 1. Sphere of Expanding Energy. The telescope aperture records and captures but a minuscule fraction of this enormous pulse of Energy.

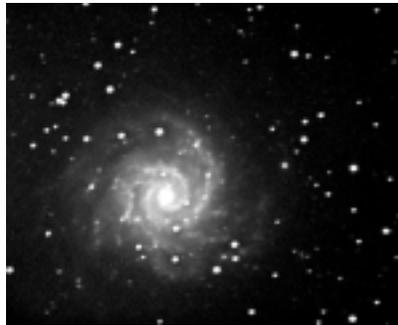


Figure 2. Photo of M74 (NGC 628) taken with 32-inch f/4 Newtonian in 1999, with an Apogee AM13 camera., by Mario Motta.



Figure 3. Photo of M74 taken in February 2002, with SN 2002ap evident in the spiral arm. Taken with the same equipment as Figure 2, by Mario Motta.