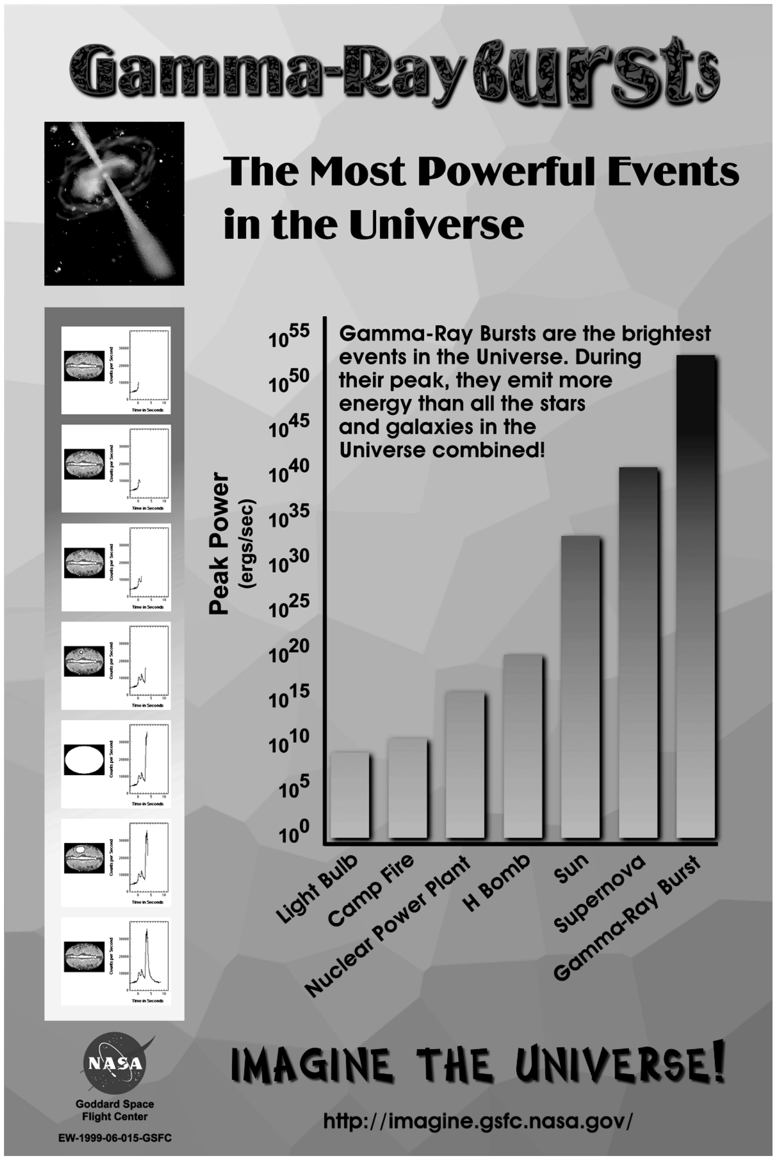

An Information & Activity Booklet

Grades 9-12

1999-2000

IMAGINE THE UNIVERSE!

Probing the Structure & Evolution of the Cosmos

http://imagine.gsfc.nasa.gov

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IMAGINE THE UNIVERSE!

Presents

Gamma-Ray Bursts

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This booklet, along with its matching poster, is meant to be used in conjunction with the IMAGINE THE UNIVERSE! Web site or CD-ROM.

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Preface

WELCOME to the third in a series of posters and activity booklets produced in conjunction with the *Imagine the Universe!* Web site. The poster/booklet sets are intended to provide additional curriculum support materials for some of the subjects presented in the Web site. The information provided for the educator in the booklet is meant to give the necessary background information so that the topic can be taught confidently to students. The activities can be used to engage and excite students about the topic of gamma-ray bursts in a number of disciplines and ways. All activities can be photocopied and distributed for educational, non-commercial purposes.

For additional materials and information, visit the *Imagine the Universe!* Web site at http://imagine.gsfc.nasa.gov/. We also look forward to hearing your opinions about this poster/booklet set! Our email address is itu@heasarc.gsfc.nasa.gov.

Gamma-Ray Bursts

I. Introduction

Perhaps the greatest mystery for astronomers who look at the sky at very short wavelengths has been the incredibly brief and intense bursts of gamma-rays from seemingly random locations in the sky. A few times a day, the sky lights up with a spectacular flash, or burst, of gamma-rays. Often, this burst outshines all of the other sources of cosmic gamma-rays added together. The source of the burst then disappears completely. No one can predict when the next burst will occur or from what direction in the sky it will come. For thirty years, astronomers have been trying to understand the nature and origin of these gamma-ray bursts (GRBs).

Gamma-ray bursts were first discovered by Ray Klebesadel at Los Alamos National Laboratory. He was working on a project responsible for monitoring the Soviet compliance with the Nuclear Test Ban Treaty. A series of satellites called *Vela* were put into orbit to perform this task. After the first 4 satellites were up, Klebesadel and his colleagues started to look through the data they sent back to Earth. Primarily, they were looking to make sure everything was working as expected and that nature was not generating any sort of signal that could trick the satellites into thinking a nuclear explosion has occurred. This was a painstaking task of looking through stacks of computer printouts by hand. In fact, instead of graphs that would quickly show what happened, Klebesabel's people had to examine columns of numbers and look for significant changes in their values. In mid-1969, Klebesadel was examining data taken on July 2, 1967. He noticed a spike in the data, a dip, a second spike, and a long, gradual tail off. "One thing that was immediately apparent was that this was not a response to a clandestine nuclear test," Klebesabel said at a conference held about GRBs in Huntsville, AL in 1998. His team checked for possible solar flares and supernovae, and found none.

After this first event was noticed, other similar events were quickly discovered in the data printouts. With the timing between *Vela 5* and *6* synchronized to within 1/64th of a second, the *Vela* team was able to triangulate the locations of the bursts by comparing differences in arrival times at widely separated satellites. They confirmed their suspicion that the bursts came from outside the solar system. Already, by their random scatter across the sky, the data hinted that the sources were out in the Universe rather than being confined in our Galaxy. By 1973, when Klebesadel and his team were ready to publish the results in *Nature* and present them at the American Astronomical Society meeting, there were at least 16 confirmed bursts.

Using a hard X-ray detector on board the *IMP-6* satellite (which was intended to study solar flares), Tom Cline and Upendra Desai of NASA/GSFC were the first to confirm Klebesadel’s findings and provide some spectral information which showed that the burst spectra peaked at gamma-ray energies. Thus the events were not simply the high-energy tail of an X-ray phenomenon. A collimated gamma-ray telescope on board *OSO-7* was also able to confirm a direction to one of the events, supporting the original conclusion of cosmic origin. These confirming results, published close on the heels of the original discovery, gave the whole scenario an aura of enhanced mystery. The excitement created in the astronomical community was evidenced by a burst of publications of instrumental and theoretical papers on the newly discovered "cosmic gamma-ray bursts".

Over the next 20 or so years, a catalog of GRBs was constructed and many theories were discussed as to their origin. Great debates were even held within the astronomical community as to whether the bursts were occurring in our Galaxy or in other galaxies. The addition of each newly observed burst tended to reveal not much more than that they never repeated from the same source. The launch of the *Compton Gamma-Ray Observatory* in 1991 ushered in a new era of GRB observations. The Burst and Transient Source Experiment (BATSE) was capable of monitoring the sky with unprecedented sensitivity. As time passed and the catalog of bursts observed by BATSE grew, one thing became clear: the bursts were in no way correlated with sources in our Galaxy. It began to be accepted that GRBs must originate in galaxies far, far away. In 1997, the Italian-Dutch *BeppoSAX* satellite made a breakthrough in our understanding of GRBs. Using a particularly effective combination of gamma-ray and X-ray telescopes, *BeppoSAX* was able to detect afterglows from a few GRBs and precisely locate the sources so that other telescopes could study the same locations in the sky. This work showed that GRBs are indeed produced in very distant galaxies, requiring the explosions producing them to be extremely powerful.

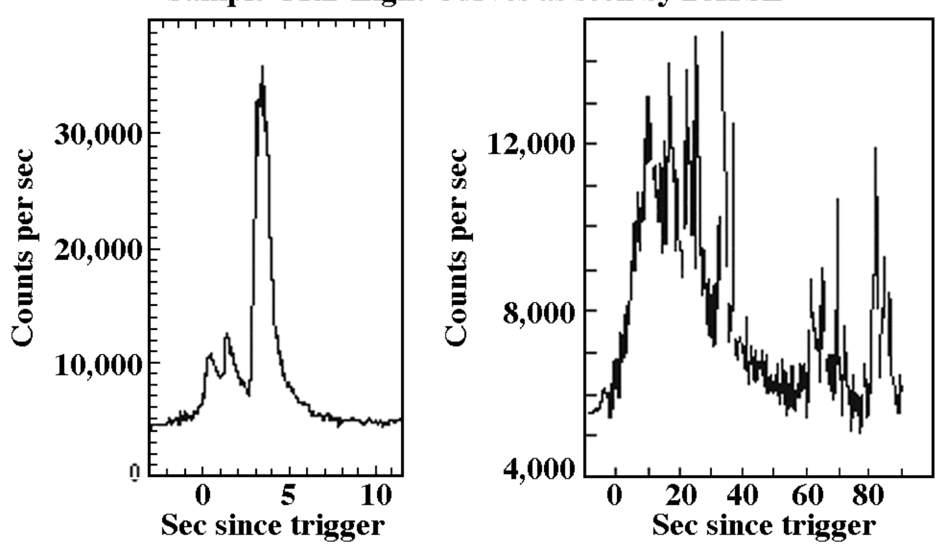
The next big breakthrough in understanding GRBs occurred when an enormously powerful event was detected on January 23, 1999 (designated GRB990123). It was observed with an unprecedented range of wavelengths and timing sensitivities. A small automated optical telescope responded to alerts from orbiting gamma-ray and X-ray telescopes to begin observing the GRB within 22 seconds of the burst's onset...while the GRB was still on-going. Subsequent observations took place over the next few weeks in the gamma-ray, UV, optical, IR, millimeter, and radio. The object was determined to have a redshift of 1.6, putting it at a cosmological distance and implying a staggering energy release. In fact, if the energy were emitted equally in all directions, twice the rest mass energy of a neutron star would be required. If the energy is being beamed out in a preferred direction that happens in this case to point directly toward Earth, however, the required energies are more reasonable and easier to explain. Multiwavelength, prompt observations of many bursts will be required in order to determine the central engine (or engines...there may be more than one mechanism!) of GRBs.

We tentatively believe GRBs are produced by material shooting towards us at nearly the speed of light, which was ejected during the collision of two neutron stars or black holes. Alternatively, the events could arise from a hypernova, the huge explosion hypothesized to occur when a supermassive star ends its life and collapses into a black hole. However, our sample size is small and our knowledge base shallow.

II. GRBs - What we know and what we don't know

1. We know what they look like in time in gamma-ray wavelengths

Sample GRB Light Curves as seen by BATSE

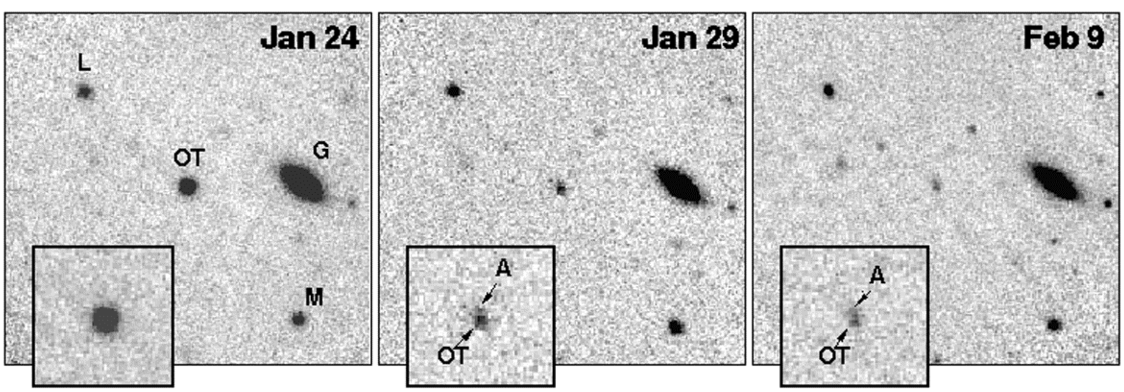


Perhaps the most striking feature of the time profiles of gamma-ray bursts is the diversity of their time structures. Some burst light curves are spiky with large fluctuations on all time scales, while others show rather simple structures with few peaks. However, some bursts are seen with both characteristics present within the same event! However, no persistent, strictly periodic behavior has been seen from gamma-ray bursts. A common quote amongst gamma-ray astronomers is “If you’ve seen one gamma-ray burst, you’ve seen one gamma-ray burst!”

The durations of gamma-ray bursts range from about 30 milliseconds to over 1000 seconds, although the duration of a gamma-ray burst is difficult to quantify since it is dependent upon the sensitivity and the time resolution of the experiment which observes the event. The "tip of the iceberg" effect tends to cause weaker bursts to be observed as shorter, since only the higher parts of the peak emission are observable.

2. We are beginning to know what they look like in other wavelengths

Gamma-ray bursts were named when they were discovered in the early 1970s; at that time, they seemed to only emit radiation in the gamma portion of the spectrum. Scientists thought it was odd that the bursts appeared to only give off one form of energy. Most other energy sources give off several forms of energy simultaneously. A flame, for instance, gives off infrared (heat) and visible light. As it turns out, gamma-ray bursts are more than just explosions emitting gamma-rays. Now we know that it was our ability to see, rather than the source, which was limited. Individual telescopes were only designed to see one part of the electromagnetic spectrum. When a gamma-ray telescope detects a burst, there was usually not enough time to direct other telescopes to look at the explosion. All of this is now changing. For GRB 990123, the ground-based Robotic and Optical Transient Search Experiment (ROTSE) coordinated with the space-based *Compton Gamma-ray Observatory* within 20 seconds of the start of the explosion - just quick enough to catch a burst in action in multiple wavelengths.



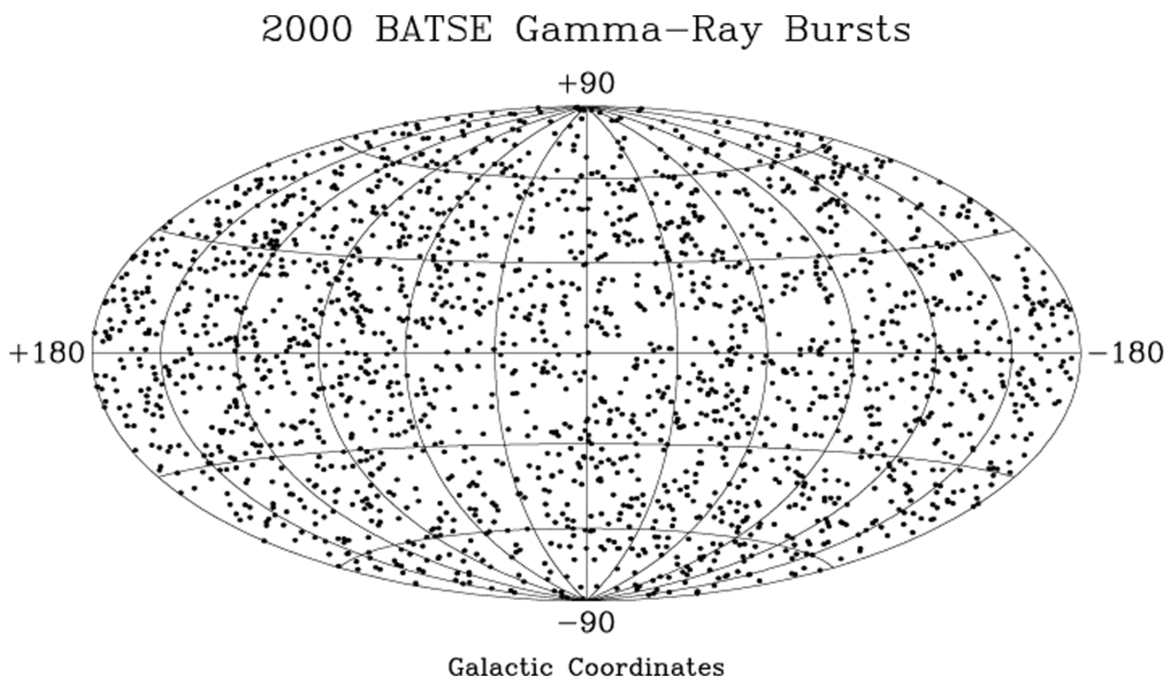
Three images from the Keck I telescope of the field of GRB 990123 (24 January 1999 UT, 29 January 1999, and 9 February 1999 UT). The image is rotated to the standard orientation, so that the east is to the left and north is up. By looking at the inset image blowups, it is clear that in the 24 Jan image, the optical transient (OT) believed to be associated with the GRB dominates the host galaxy flux, but by 29 Jan the galaxy is resolved from the OT.

Although the explosion only lasts for a few seconds, the afterglow of a GRB can linger for weeks or even months. The afterglow follows a path down the electromagnetic spectrum, first mostly emitting gamma-rays, then peaking at X-rays, and so on, all the way down to radio waves. Eventually, the afterglow fades completely from our view. Because the afterglow is much longer-lived than the initial explosion, various types of telescopes have been used to study the afterglow. Most of our recent insight about gamma-ray bursts comes from studies of the afterglow, although interpretations of the data are still widely debated.

Every aspect of a burst, from the kind of radiation emitted to the intensity of the explosion, tells its own tale. By figuring out how all these different "points-of-view" fit into the main event, scientists hope to determine what really happens. With GRB 990123, scientists saw for the first time visible light emitted during a gamma-ray burst explosion. Although the burst was 9 billion light years away, the light was so bright observers on Earth could've seen it with a pair of binoculars. Scientists see the emission of this intense visible light as a clue that helps determine the structure of the explosion. Because material is flowing out from the explosion at different velocities, collisions occur. Such collisions in a gamma-ray burst create shock waves that generate various energy wavelengths.

In fact, scientists believe that three kinds of shock waves are associated with gamma-ray bursts: external, internal, and reverse. As the source of a gamma-ray burst explodes, material blows outward, creating an external shock wave traveling away from the source of the explosion. The impact of this fast-moving material pushing against the interstellar medium creates reverse shock waves. Meanwhile, matter still racing outward from the explosion at different speeds generates internal shock waves. These internal shock waves push the reverse shock waves outward. The reverse shock waves still appear to be traveling inward, however, because they are slower and colder than the internal shock waves.

3. We know that they come from every direction in the sky…and from very far away!



The random occurrence of GRBs has been one of the biggest problems with studying them -- we never know where the next burst will come from! In the beginning, scientists thought that the sources of GRBs would all be in our Milky Way Galaxy. This would then cause the distribution of GRB locations to be concentrated along the galactic plane (a line running between (+180 and –180 in the image above). Today, primarily through the data from the BATSE experiment, we know that bursts come from all over the sky with equal probability. And the whole sky is a very big place to try to watch all at once!

Although a long debate had been held concerning whether gamma-ray bursts came from our own Solar System, the Milky Way Galaxy, or much further away, the years 1997 through 1999 provided observations with uncontroversial evidence that GRBs come from the distant reaches of the cosmos. By watching the fading of the optical counterparts of that bursts, astronomers were able to conclude that the explosions were embedded in faint galaxies. For example, a day or so after GRB990123, astronomers used the 10-meter Keck II telescope on Mauna Kea to analyze ultraviolet and visible light from the fading afterglow. Their data showed that the explosion took place about 9 billion light years from Earth!

3. We Don’t Know if the Radiation is Beamed

The amount of energy released from a gamma-ray burst boggles the imagination. Exploding with the power of ten million billion suns, only collisions between objects like super-dense neutron stars and black holes have enough energy potential to create such a cataclysmic event. But no one is sure what causes a gamma-ray burst; the mechanism remains a mystery.

As powerful as all gamma-ray bursts are, GRB 990123 was at the top 1 percent of its class. GRB 990123 was so powerful that scientists began to wonder if the light in the burst was beamed rather than dispersed evenly, or isotropically. A beamed explosion is directed like a flashlight, while an isotropic explosion is dispersed outward like the emission from a light bulb. Beaming is actually quite common in the emissions from astronomical objects. Data from the *Hubble Space Telescope* showed a rapid decline in the optical brightness associated with GRB 9990123. These data provide evidence for the beaming theory, because beamed light appears to dim much more rapidly than isotropic light. A beamed explosion would have all of its power concentrated to a specific area. But an isotropic burst explodes outwards to all points in space, so we would only see the part of the energy directed toward us. Isotropic explosions, therefore, are more powerful than they look. The calculation of a gamma-ray burst's total energy depends on the dynamics of the explosion - an isotropic explosion would be calculated to have much more power than a beamed burst.

If gamma-ray bursts are beamed, the energies we're seeing are less than we first thought, but that also means there are more of them out there that we don't see. If the explosions are beamed in just one direction, only those observers located along the path of the beam would see them. That means that there could be gamma-ray bursts exploding all the time, but because the beams are focused in other directions we don't see them. All is not lost, however! Regardless of whether or not we see the beams of gamma-rays, we would still be able to see their afterglows, because afterglows are always isotropic. If we find afterglows without seeing the initial bursts, that would prove gamma-ray burst explosions are beamed.

4. We Don't Know What Causes GRBs

For one brief moment, long ago in a far-away galaxy, a titanic explosion poured a torrent of gamma-rays into space. Some 12 billion years later--Dec. 14, 1997--this flash of radiation reached Earth. Headlines in newspapers and magazines, dubbed this gamma-ray burst "the most powerful explosion since the Big Bang." While that may be hyperbole (brighter bursts have been observed since) researchers have calculated that this cosmic flash packed 100 times more energy than a supernova explosion and calls into question the popular theory in which GRBs are generated when two neutron stars collide and merge, forming a black hole. Dale A. Frail of the National Radio Astronomy Observatory in Socorro, N.M., noted that to generate the energy associated with the Dec. 14 burst, a large fraction of the rest masses of both neutron stars had to have been converted into gamma-rays. Scientists find this unlikely.

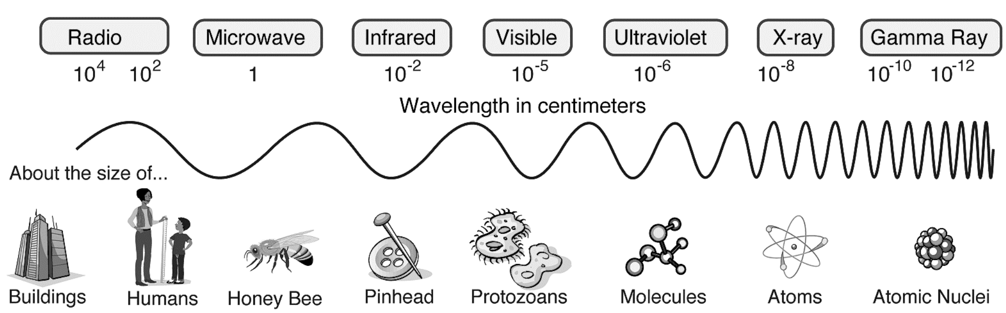
Other damning evidence against this model was discovered in a later GRB – astronomers glimpsed an afterglow at radio wavelengths before finding it in visible light. Such a sequence of events suggests that the burst originated from a place containing a great deal of dust, which blocks visible light but is transparent to radio waves. Stellar nurseries (areas of new star formation) are rich in dust, and previous studies have hinted that several other bursts originated in star-forming locales. Neutron stars probably do not merge within star-forming regions. During the 100 million years or so that it takes for neutron stars to form and merge, they would migrate far from their birthplaces.

Dr. Bohdan Paczynski of Princeton University and many other astronomers now favor another model called a hypernova explosion. Still considered a hypothetical notion, a hypernova may emit 100 times more energy than a supernova. What causes a hypernova remains unknown, although astronomers have proposed that they happen when a very large and rapidly rotating star collapses directly into a black hole.

It is likely that both the neutron star merger theory and the hypernova theory are correct. Future observations will be able to tell, as well as determining if the Universe generates GRBs via other circumstances as well.

III. The Electromagnetic Spectrum as a Probe of Gamma-Ray Bursts

To understand gamma-ray bursts, you must first understand that gamma-rays are the most energetic form of light. Light is the familiar word for what physicists call electromagnetic radiation or electromagnetic waves. Light is a form of energy; it can travel through empty space and is in the form of individual wave packets called photons. The waves in packets of visible light are tiny ripples less than a millionth of a meter long. When visible light is split up into its different wavelengths, the result is called a spectrum. Violet light has the shortest wavelength and red light has the longest – about twice as long as violet. Visible light is not the only form of electromagnetic radiation, however. The electromagnetic spectrum extends beyond the colors of the rainbow in both directions – to much shorter wavelengths than the violet and to much longer wavelengths than the red. At the longer wavelengths are radio waves, microwaves, and infrared radiation. At the shorter wavelengths are ultraviolet radiation, X-rays, and gamma-rays.



To understand the Universe, astronomers look at all wavelengths; the cosmic sky has a totally different appearance at different wavelengths of light. At radio wavelengths, astronomers see distant quasars and hot gas in our Milky Way Galaxy. The infrared sky shows mainly tiny dust particles strewn through our Galaxy and other galaxies. Visible and ultraviolet show mainly the light from ordinary stars. X-rays reveal gas heated to millions of degrees lying between galaxies or falling onto compact objects like neutron stars and black holes. Gamma-rays can be produced only by extremely energetic phenomena, and we see several types of gamma-ray emission in the sky. Gamma-rays seen along the plane of the Milky Way are not from ordinary stars, but from nuclear reactions generated by protons accelerated to nearly the speed of light slamming into gas lying between the stars. Gamma-rays are also seen from blazars -- intense beams of light and particles pointed directly at the Earth produced by massive black holes in distant galaxies. Gamma-rays can be detected in the magnetic flares on the surface of our Sun, and by the radioactive decay of short-lived atomic nuclei produced by supernova explosions in the Galaxy.

All objects in our Universe emit, reflect, and absorb electromagnetic radiation in their own distinctive ways. The way an object does this provides it special characteristics which scientists can use to probe an object’s composition, temperature, density, age, motion, distance, and other chemical and physical quantities. While the night sky has always served as a source of wonder and mystery, it has only been in the past few decades that we have had the tools to look at the Universe over the entire electromagnetic (EM) spectrum and see it in all of its glory. Once we were able to use space-based instruments to examine infrared, ultraviolet, X-ray, and gamma-ray emissions, we found objects that were otherwise invisible to us (e.g., black holes and neutron stars). A “view from space” is critical since radiation in these ranges cannot penetrate the Earth's atmosphere. Many objects in the heavens “light up” with wavelengths too short or too long for the human eye to see, and most objects can only be fully understood by combining observations of behavior and appearance in different regions of the EM spectrum.

We can think of electromagnetic radiation in several different ways:

• From a physical science standpoint, all electromagnetic radiation can be thought of as originating from the motions of subatomic particles. Gamma-rays occur when atomic nuclei are split or fused. X-rays occur when an electron orbiting close to an atomic nucleus is pushed outward with such force that it escapes the atom; ultraviolet, when an electron is jolted from a near to a far orbit; and visible and infrared, when electrons are jolted a few orbits out. Photons in these three energy ranges (X-ray, UV, and optical) are emitted as one of the outer shell electrons loses enough energy to fall down to the replace the electron missing from the inner shell. Radio waves are generated by any electron movement; even the stream of electrons (electric current) in a common household wire creates radio waves ...albeit with wavelengths of thousands of kilometers and of very weak amplitude.

• Electromagnetic radiation can be described in terms of a stream of photons (massless packets of energy), each traveling in a wave-like pattern, moving at the speed of light. The only difference between radio waves, visible light, and gamma-rays is the amount of energy in the photons. Radio waves have photons with low energies, microwaves have a little more energy than radio waves, infrared has still more, then visible, ultraviolet, X-rays, and gamma-rays. By the equation $E=hf$, energy dictates a photon’s frequency and, hence, wavelength.

The value of the EM radiation we receive from the Universe can be realized by considering the following: Temperatures in the Universe today range from 10^{10} Kelvin to 2.7 Kelvin (in the cores of stars going supernova and in intergalactic space, respectively). Densities range over 45 orders of magnitude between the centers of neutron stars to the virtual emptiness of intergalactic space. Magnetic field strengths can range from the 10^{13} Gauss fields around neutron stars to the 1 Gauss fields of planets such as Earth to the 10^{-7} Gauss fields of intergalactic space. It is not possible to reproduce these enormous ranges in a laboratory on Earth and study the results of controlled experiments; we must use the Universe as our laboratory in order to see how matter and energy behave in these extreme conditions.

As we develop better observing technologies and techniques for gamma-ray astronomy, we can ask and answer fundamental questions about GRBs, such as:

• What are the progenitors of GRBs? Where are the objects which lead to GRBs located within their host galaxies? What is the local environment like at that location?

• Are there different classes of bursts with different underlying physical processes at work?

• Can GRBs be used to probe the early Universe? Can we use the optical/X-ray afterglows as high redshift beacons? Can we use the X-ray emission to probe the intergalactic and intercluster media?

IV. Activities

1. Apparently, They Are Absolutely Bright

At a press conference discussing the event GRB 990123, Dr. Chryssa Kouveliotou of Universities Space Research Association at the Marshall Space Flight Center said "If the burst had occurred somewhere in our galactic neighborhood, it would have been so bright that night would've turned into day." What exactly does this tell us about how bright it was?

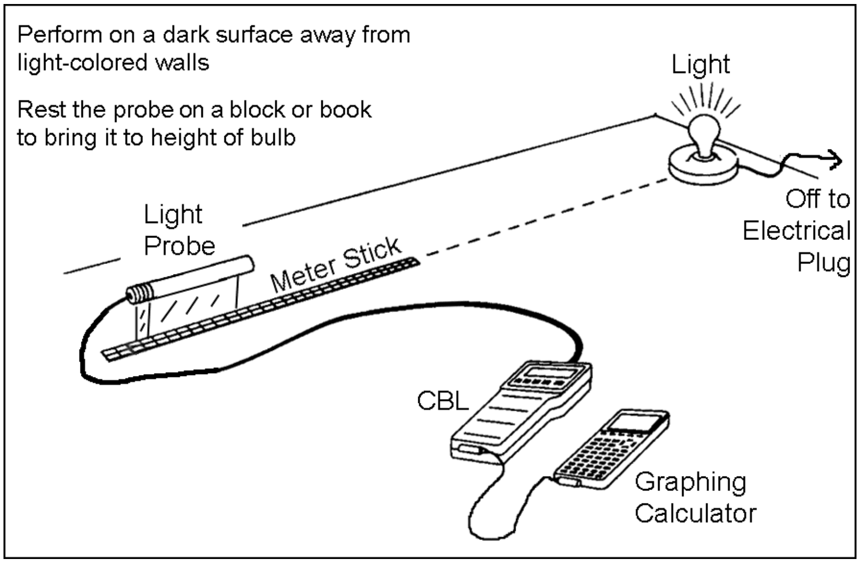
Astronomers express the brightness of stars in visible light in two related forms. Apparent visible magnitude, m_V, measures the light that reaches us on Earth. This measure, however, is not a true measure of brightness because distance makes things appear dimmer and apparent magnitude does not correct for this effect. Absolute magnitude, M_V, is a true measure of how much light an object is actually producing. Determining how bright the star (or galaxy or any other emitter) would be if it were located 32.6 light-years (10 parsecs) away compensates for the effect of distance. Note that here we assume space is completely transparent in all directions, so only distance affects what we detect. If clouds of dust intervene between the emitter and us (as they usually do), we have to compensate for that effect too!

Electromagnetic radiation (regardless of whether it is in the form of radio waves, infrared, or gamma-rays) has a common property called the inverse square law. This law states that the amount of energy that is measured by a given detector put at a given distance from an emitter is proportional to the inverse square of the distance from the emitter to the detector. Think about it this way. An emitter E is sitting a distance R away from a detector D. The emitter is radiating equally in all directions. Place an imaginary sphere of radius R around the emitter. The emitter releases a certain amount of energy in 1 second. This energy travels outward in all directions such that in a time T, it reaches the surface of the imaginary sphere a distance R away. This means that now, the original energy, let us call this amount O, is spread out equally over the surface of a sphere of radius R. The surface area of a sphere of radius R is equal to $4\pi R^2$. Thus, the amount of energy passing through each square centimeter of the sphere is $O/4\pi R^2$, if R is measured in centimeters. We see, then, that the amount of energy passing through a unit area decreases with the square of the distance from the source. This is the inverse square law of light propagation.

It is important to realize that we now have something to consider when we analyze our observations of the Universe: an object may appear bright because it really is, or it may be bright because it is close by. Conversely, an object may appear dim because it really is, or else it could be just very far away. Such thinking played an important role in the history of understanding GRBs. When they were first detected and their enormous energies calculated, it was believed that they had to be located in our Galaxy. The amount of energy they would be required to produce if they were very far away was just too difficult to seriously consider. Now, however, we know that in fact they are at cosmological distances - that is, very far away indeed. Scientists are still working hard to understand how the enormous energy required for us to be able to detect them from so far away (with the energy falling off as $1/R^2$) is created. Beaming, which means the energy is not emitted equally in all directions, but instead in a narrowly defined, preferred direction is the most probable answer.

It is easy to demonstrate the fall off of light in your classroom with a graphing calculator, Calculator-Based Laboratory (CBL™), and light probe. In the exercise, you will measure the intensity (or brightness) of a light as it is moved away from the light probe of the CBL. The resulting data can be graphed and analyzed. For detailed discussions of an activity of this type, see

Real-World Math with the CBL™ System, Activity 7, Light at a Distance
Exploring Physics and Math with the CBL™ System, Activity 43, Intensity of Light
Physical Science with CBL™, Experiment 25, How Bright is the Light?



In short, place a 40W (or less) bulb in a shadeless lamp or socket. Put a meter stick at a known distance about 2 meters away from the bulb and on the same level. Place the light probe next to the end of the meter stick closest to the bulb. Make sure nothing obstructs the path between the two. Darken the room. Run the appropriate program on the TI-83 (either BULB, LIGHT, or PHYSCI) and follow the directions it gives you. Make a measurement, then move the probe such that the distance to the bulb increases about 10 cm. Repeat until you have 10 measurements. Plot the intensity values you measured as a function of distance.

• What form do your data take? Linear? Power Law? Quadratic?

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• Now fit your data using your graphing calculator. What happens to the shape of the line if the fitting parameters become larger? Smaller?

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Perform the experiment again with either a brighter or dimmer bulb. Consider also taking data at different distances. You should now be able to discuss the following:

• When an astronomer measures the brightness of an object in the Universe, what sort of conclusions can be made about the energy being emitted by that object? What additional information would help the astronomer?

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Extensions:

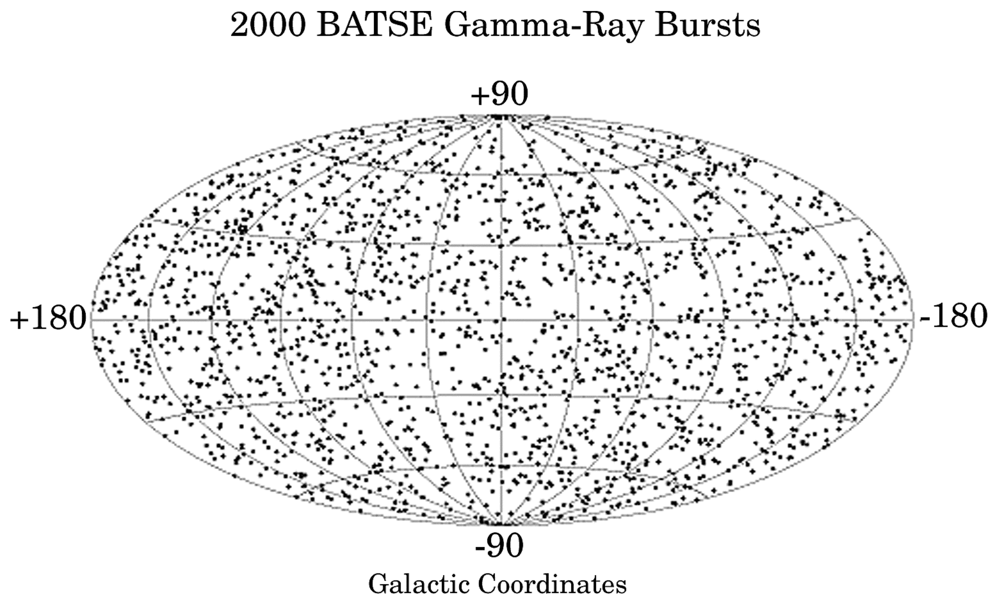
• Investigate the magnitude scale in depth -- learn about Norman R. Pogson; learn about the mathematical equation that relates the magnitude values and fluxes of different objects; learn about where our Sun ranks on the magnitude scale.

• Investigate what astronomers call the *distance modulus* and use it to determine how bright a star would be on the magnitude scale as you move it closer or further away from Earth. What effects would intervening dust have on this calculation?

2. It's Either Probable, or It's Not

Imagine looking up at the night sky with an ordinary telescope. What do you see? Constellations of stars, possibly a satellite orbiting Earth, and maybe a planet or two. But now think about looking with a magical telescope that would allow you to see gamma-rays-- the most energetic form of radiation. Among many exotic phenomena, chances are you would see an event called a Gamma-Ray Burst or GRB!

A Gamma-Ray Burst is a phenomenon that comes from the hottest, fastest, densest, or most powerful objects in the Universe! A burst will last anywhere from 0.01 to 1000 seconds, during which time it will be the brightest source in the gamma-ray sky. Sometimes a burst is brighter than all the rest of the gamma-ray sky added together! GRBs occur a few times a day at a *random* time and from a *random* direction in the sky (see below).



1. Examine the image above. It shows the location in the celestial sphere of 2000 GRBs as seen by the BATSE experiment onboard a NASA gamma-ray astronomy satellite. Do you see a pattern to the distribution of locations of GRBs?______________________________________

   Move into your groups of two, and discuss this with your partner.

2. Approximate a projection of the celestial sphere by a circle. Draw this circle with radius of 4 inches and on a blank sheet of paper.

3. Imagine now that *you* are designing a "magical" telescope or Gamma-Ray detector. Assume your detector will see 1/5 of the circle at any time (Realistically, all detectors have limitations!).

   You may select any part of the circle that would represent 1/5 of the area of the circle. Color this area in with a red pencil.

4. What would be the theoretical probability that your detector would observe a given Gamma-Ray Burst? ________________

5. Now remove everything from your desk except your drawn circle. One person should be the "circle holder", the other should be the "burst marker". With marker in hand (felt tip exposed pointing down), and eyes closed, the "burst maker" should begin randomly dropping the marker until the circle has 50 marks in it (some marks may be outside of the circle). The "circle holder" should keep the circle centered on the desk and ensure that the "burst marker" is moving his/her arm randomly up-down-left-right before dropping the marker.

7. Now examine your marked circle. What is the experimental probability that a GRB occurred in your detector's area? ________________

8. Explain what you think would happen after 100 trials.
____
____
____

   What about 1000, or 10,000?
____
____
____

9. Imagine you are the Principal Investigator for the next generation Gamma-Ray astronomy satellite. Use what you've learned in this investigation to design your satellite

Think about these questions...

• Do you need to look at the whole sky all the time or can you look at a smaller part of the sky for a longer interval and achieve the same result?

• What are the advantages and disadvantages of each approach?

Now explain your mission to Dr. Gam A. Ray. Note that spelling and grammar count along with a well thought out and explained mission.

The origin of the GRB is one of the most fascinating mysteries of modern astrophysics. The amount of energy released in a burst can be greater than the rest-mass energy of the Sun, and momentarily creates the most extreme conditions in the Universe since the Big Bang. GRBs can generate up to 10^{53} ergs/second! In the past few years, astronomers have begun to make small inroads to the origin of GRBs. It may be the result of the merger of two compact objects like neutron stars or black holes, or of a more exotic event called a hypernova. None of these theories have been observationally confirmed. In fact, current instruments cannot tell us the answer. It will depend on the next generation of detectors and telescopes to solve the mystery of gamma-ray burst.

3. Blast from the Past

Dr. Shri Kulkarni of the California Institute of Technology and his colleagues found that a certain gamma-ray burst came from a faint galaxy with a redshift of 3.4. “That means that the burst originated over 12 billion light-years away," Dr. Kulkarni said. How did he know that?

Redshift is a term astronomers often use for the Doppler Shift observed in the spectra of celestial objects. Two things can create the shift - the motion of the object toward or away from the observer, or motion near a strong gravitational field. The Doppler effect is named for Christian Doppler (1803-1853), who pointed out that if a light source is approaching or receding from an observer, the light waves will be (respectively) crowded together or spread out. Consider this: if the light source is stationary with respect to the observer, it will emit wave crests of light at regular intervals 1,2,3,4, and spread out in all directions evenly. However, if the source is moving toward the observer, successive wave crests are emitted from different, shorter distances from the observer. To the observer, this has the effect of making the waves appear shortened...and shorter wavelengths appear toward the blue end of the spectrum. The opposite effect occurs if the emitter is moving away from the observer, the distance between crests appears to be lengthened - or shifted toward the red end of the spectrum.

If the motion is entirely either directly toward or away from the observer, the equation which relates the velocity of the motion to the apparent shift in wavelength is:

$$\Delta\lambda/\lambda = (\mathrm{sqrt}(1+v/c) / \mathrm{sqrt}(1-v/c)) - 1$$

$\Delta\lambda$ is the difference between λ the emitted wavelength and the wavelength measured by the observer, c is the speed of light, and v is the relative line of sight velocity of the observer and source (it is counted as positive if the velocity is away from the observer and negative if the velocity is toward the observer). If the relative velocity is small compared to the speed of light, this equation reduces to the more common and simpler form

$$\Delta\lambda/\lambda = v/c$$

In astronomy, the Doppler shift is a very powerful tool from which can lead us to know not only how fast something is moving, but also how far away from us it is. Between 1912 and 1925, Astronomer V.M. Slipher at the Lowell Observatory first measured the radial velocities of galaxies using the Doppler shift. He discovered that they all seemed to be moving away from us...the Universe was expanding! By 1929, Edwin Hubble at the Mt. Wilson Observatory determined the distances to galaxies for which velocities had been measured and found that these two parameters were proportional to each other. This relation is now known as the Hubble law. It can be written as $v = Hr$, where r is the distance, H is the constant of proportionality called the Hubble constant, and v is the velocity. The Hubble constant is currently believed to be between 60 and 75 km/s per million parsecs.

What do the redshifts (which astronomers define as $\Delta\lambda/\lambda$) have to do with GRBs? Try this:

In a few cases, shortly after the detection of a GRB, high-powered ground- and space-based observatories were able to detect the afterglow of the event. These observations provided scientists with the data to determine the host galaxy of the event and obtain a redshift measurement of that galaxy. Redshift measurements allowed a determination of the distance to the source of the GRB!

• Examine the table below. Use what you have learned about redshift to determine the velocities and distances of the galaxies which appear to host the GRB events. Perform these calculations with both the minimum and maximum Hubble constant values. HINT: The material associated with GRBs is moving very, very fast – so the simplified version of the Doppler shift equation cannot be used.

Burst	**Redshift**
970508	0.835
971214	3.418
980703	0.966
990123	1.6

• Given your knowledge of how fast gamma-rays travel, how long has it taken them to reach us from such a distance?

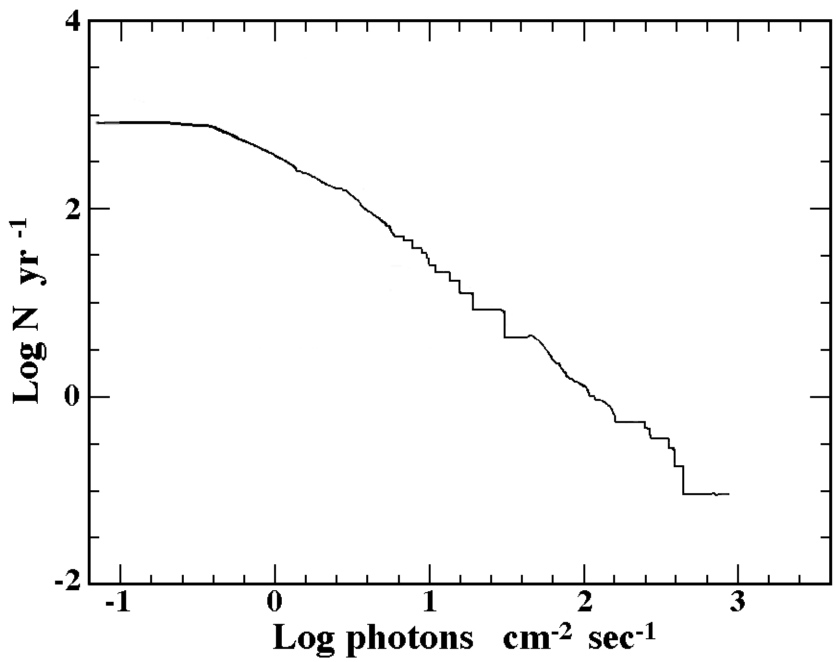
• What does this tell us about the age of the Universe?

• What must have happened in the Universe already in order for a GRB to occur?

4. A Sensitive Situation

In order to study a cosmic phenomenon, there are several factors to consider when designing your detector system. One is how bright the phenomena are that you will be studying. Related to this is how often an event of a given brightness occurs. If you don't understand these things, you could look for a very long time and see nothing...or you could be blown away by the first event!

Examine the plot below. Note that it is a Log-Log plot, so think carefully in trying to answer the questions below. On the X-axis you see the number of photons per square centimeter per sec detected from a GRB (this is merely a measure of its brightness) and on the Y-axis you see the number of bursts each year which are that bright or brighter. These bursts can occur anywhere in the sky. So we will assume that our detector is located far from Earth and can continuously view the entire celestial sphere.



1.) If your detector can measure bursts which are 100 photons per cm^2 per sec or brighter, how many GRBs would you detect each year?

____

2.) If you are designing a new detector and want to be able to detect about two GRBs per week, what are the dimmest bursts that you would detect? What does this mean about how sensitive a detector you must design?

____

3.) If your detector is 100 times more sensitive than what you found in (1), how many GRBs would you detect each week?

____

5. When You're Hot, You're Hot…Unless You're Not!

Most of the information we have about the Universe was obtained by detecting the radiation the object or event emits. This radiation may be the result of a thermal, nuclear, or electromagnetic process. In this activity, we concentrate on the thermal process, that is, things emit radiation because they are hot and trying to cool off.

Let us think about what can happen when electromagnetic radiation is incident upon an object. Three things can happen to the radiation: it can be reflected, transmitted, or absorbed. *Unless the object is transparent, the transmitted radiation is negligible compared to what is absorbed or reflected, so we'll ignore it here.* The energy of the absorbed radiation serves to heat the object, which causes the object to begin to radiate away this heat at some point. Thus, it can be said that an opaque object such as a planet can be seen both by the radiation it reflects and by the reradiated energy that it had previously absorbed.

How the total energy of the reflected radiation from an object is distributed in energy (or wavelength) is determined by the absorbing properties of the object. If for example, white light is shone upon the object and it preferentially absorbs longer (red) wavelengths, the object will appear to be blue. Many complicated factors determine the nature of the reradiated energy from the object, but the most important is the temperature, especially if the object is in equilibrium (i.e., it is absorbing and radiating at the same rate so the temperature is constant). To avoid all these complications, scientists often refer to something called a "blackbody". This is a hypothetical, idealized body (or object) that absorbs all of the electromagnetic radiation incident upon it. Its temperature then depends only on the amount of energy striking it and the spectral distribution of the energy it reemits can be exactly calculated by the radiation laws of physics. Here are the main three laws:

Planck's Radiation Law --- $E(\lambda,T) = (2hc^2/\lambda^5)\ (1/(e^{hc/\lambda kT} - 1))$ gives the radiant energy E emitted per second at any wavelength λ by 1 square centimeter of a blackbody at any temperature T. The energy is in ergs, the temperature is in Kelvin, the wavelength is in centimeters, and the Boltzmann constant k is $1.37\text{x}10^{-16}$.

Wien's Law --- λ_{max} = constant/T where the wavelength is in centimeters, the temperature in Kelvin, and the constant is equal to 0.2897.

Stephan-Boltzmann Law --- $E(T) = \sigma T^4$ where E is the total energy emitted per second per square centimeter by a blackbody at temperature T. If T is in Kelvin and E(T) is in ergs/cm^2/sec, then σ (the Stephan-Boltzmann constant) is equal to $5.672\text{x}10^{-5}$.

It is important to note that a blackbody, being a perfect absorber and radiator, is not necessarily black! At room temperature, it would radiate in the infrared and would indeed appear to be black (since our eyes cannot see infrared). However, a blackbody with a temperature of thousands of degrees would be very bright indeed. Stars are fair approximations of blackbodies because they are composed of hot gases that are very opaque. Because of the high opacity of the gases, the light from a star closely resembles that of a perfect radiator. It is not a perfect fit on the small scale features, but it is a good approximation of the average of all the star's photospheric layers.

What does this tell us? It tells us that objects of different temperatures can preferentially emit most of their radiation in a different part of the electromagnetic spectrum. In other words, if you want to best see an object of a certain temperature, there is a preferred part of the EM spectrum in which to do the observation!

Consider the set of blackbody curves shown below.

You will notice that for each different temperature (3000 K, 6000 K, and 10,000 K), there is a peak in the amount of power measured at a given wavelength. This peak shifts into different parts of the EM spectrum, depending on the temperature.

• Calculate how hot you would have to be to emit thermal blackbody radiation which peaks in gamma-rays (take 10^{-12} meters as your wavelength of interest).

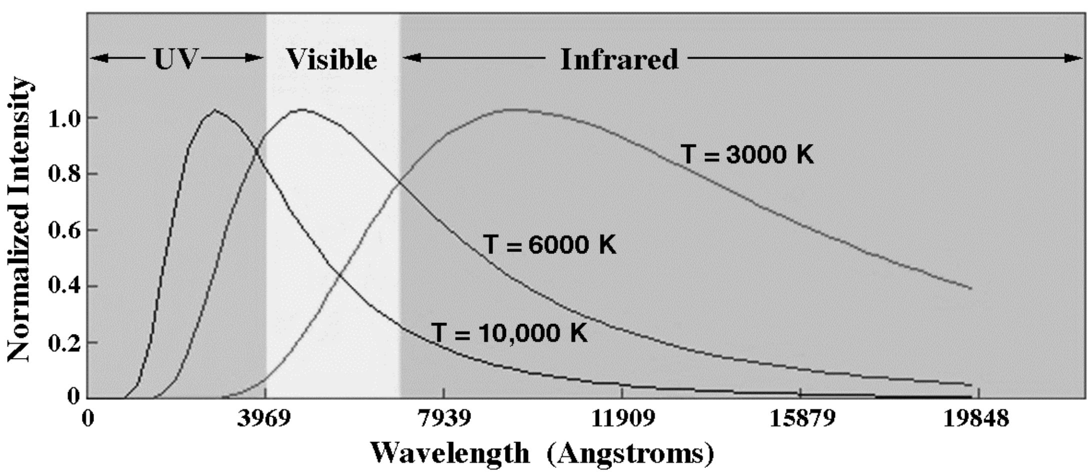
____

• Compare this value to the hottest things you can think of. For instance, you might consider the center of the Sun.

____

• What conclusion might you be led to concerning the gamma-rays from a gamma-ray burst being thermal in nature?

____



6. Behind The Gamma-rays

As unbelievable as it may sometimes seem, gamma-ray astronomers are real people too! Below you will find brief introductions to 4 well-known gamma-ray astronomers, Drs. Thomas Cline, Neil Gehrels, Kevin Hurley, and Chryssa Kouveliotou. Their stories run the entire history of gamma-ray astronomy, and their work has helped us to understand the high-energy Universe a little bit better. But you have to be truly logical to discover some of their more personal preferences!

Dr. Thomas L. Cline

Dr. Cline was conceived in Manchuria on his mother's third trip around the world, but she traveled to Peking China to the only maternity hospital she trusted in the Orient to have him born. He graduated from Hiram College in Ohio with a major in mathematics, and from St. Lawrence University. in New York State for an extra year of physics. He obtained his PhD from MIT in Physics in Jan. 1961. Cline's PhD thesis became the first published experiment in gamma-ray astronomy, from a 1960 balloon-borne 1000-lb instrument to search for cosmic gamma-rays. This experiment established the first valid upper limit, but made no positive detection.

After graduation, Dr. Cline joined the cosmic ray group at NASA’s Goddard Space Flight Center. After 12 years of research on solar flares and interplanetary particles, the confirmation of the discovery of GRBs in 1973 brought him back to gamma-ray astronomy. His Helios-2 instrument, launched in January 1976 and put into an orbit 2 AU from the Sun, was the first experiment flown to study GRBs. By combining data from Helios-2 with Earth-orbiting satellite data, it was shown that GRBs could not have originated from known X-ray emitters or from any other previously identified sources. Dr. Cline also speculated that there was a different type of gamma-ray transient being detected, one uniquely separate from other GRBs. Thirteen years later, it finally became understood that these soft gamma repeaters (SGRs) were indeed a separate phenomenon, when the Japanese ASCA satellite was pointed at a supernova remnant and saw one occur.

When asked what he prefers to do in his time away from work, Dr. Cline included in his list “I like to read, watch classic movies, and play with my grandchildren.”

Dr. Neil Gehrels

Dr. Neil Gehrels is currently the Head of the Gamma-ray & Cosmic ray Astrophysics Branch at NASA’s Goddard Space Flight Center. He received bachelor’s degrees in Music and in Physics from the University of Arizona in 1976. He obtained his PhD in Physics from the California Institute of Technology in 1981. He has served as the *Compton Gamma-ray Observatory (CGRO)* Project Scientist since 1991 and the *INTEGRAL* Mission Scientist since 1995. *CGRO* is one of NASA's Great Observatories and is the first mission to comprehensively survey the gamma-ray sky. Dr. Gehrels is active in some NASA advisory committees and is the Secretary/Treasurer of the Division of Astrophysics of the American Physical Society. His wife, Ellen Williams, is a professor of physics in the surface physics group at the University of Maryland. The Gehrels have two children, Tommy and Emily, born in 1987 and 1990.

Dr. Gehrels is a research scientist in gamma-ray astronomy active in instrument development and data analysis. His interests include nuclear astrophysics, active galaxies, and black holes. He is also the Principal Investigator for a new NASA mission called *Swift*. *Swift* is a mission that will study GRBs.

Dr. Kevin Hurley

Dr. Kevin C. Hurley received his BA in Physics from the University of California, Berkeley in 1966. Four years later, he received his PhD in Physics from the same institution. He has authored or co-authored over 450 articles in refereed journals, books, and conference proceedings. Currently, he holds the titles of Research Physicist and Space Sciences Laboratory Senior Space Fellow at UC Berkeley. He is the principle investigator for the solar and cosmic gamma-ray burst experiment aboard the *Ulysses* spacecraft.

About himself, Dr. Hurley says, ”I run the *Ulysses* GRB experiment, which is in a heliocentric orbit. I also compare my data with the data from other spacecraft such as *CGRO, KONUS-WIND, SAX*, *NEAR*, etc. This keeps me on the road a lot, but when I'm home, I like to work on my house or my old cars.” Dr. Hurley is just being modest about his accomplishments. He founded and still heads the Interplanetary Network (IPN), which uses spacecraft in both Earth-orbit and elsewhere in the solar system to establish the locations of GRBs. Before the detection of afterglows in other wavelengths, the triangulation method used by data from the IPN provided the most sensitive determination of locations of the events.

Dr. Chryssa Kouveliotou

Dr. Kouveliotou received her Diploma in Physics from the University of Athens, Greece, in 1975. She later received her PhD in Astrophysics at the Max-Planck Institute of Extraterrestrial Physics and Technical University of Munich, Germany, in 1981.She has been working on gamma-ray bursts since the start of her Ph.D. work in 1978; current research projects include ground-based follow-up observations of GRBs, X-ray studies of X-ray binaries and soft gamma repeaters (SGRs), and variability studies of accreting black holes. In a recent paper she established the connection of SGRs with young neutron stars with superstrong magnetic fields (magnetars). She has co-authored over 250 papers in refereed journals and conference proceedings, and is co-editor of 2 books. Presently, she is a Senior scientist at the Burst and Transient Source Experiment (BATSE) on the *Compton Gamma-ray Observatory*. In addition, she serves as the Director of the USRA Astronomy program in Huntsville and the Deputy Director of the Institute for Space Physics, Astrophysics and Education (ISPAE), a co-operative agreement between NASA’s Marshall Space Flight Center and the University of Alabama in Huntsville.

Dr. Kouveliotou is an avid cook. She finds it especially challenging to figure out how to incorporate her native Greek cooking into the fresh produce available in US supermarkets. Her husband, astrophysicist Jan van Paradijs, serves as the “taste tester” for her creations. She is also interested in the origins and evolutions of languages, and archeology. Currently, she is trying to learn how to garden in the Alabama climate.

Activity

When asked, Drs. Cline, Gehrels, Hurley, and Kouveliotou told us a little about what they consider their jobs to be, what their favorite kinds of food are, and what they enjoy doing in their time away from work. See if you can match each scientist to his or her preferences!
Here are your clues:

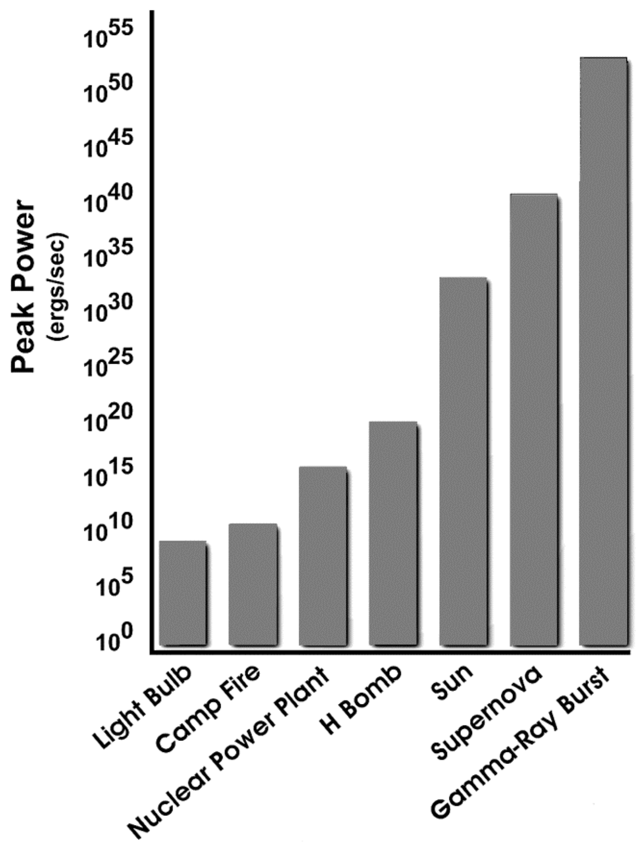
• Dr. Kouveliotou likes Greek food, but in her spare time she prefers not to travel.
• Dr. Cline is an experimental physicist.
• The scientist who likes Italian food is neither an experimental physicist nor a hardware designer.
• The scientist who does not like Italian or Japanese food enjoys listening to classical music.
• Dr. Hurley is a data analyst/archivist.
• The hardware designer enjoys mountaineering, but not Greek food.
• The scientist who loves to eat fruits and veggies enjoys flying airplanes.
• Two of the scientists are data analysts/archivists.

You can use the chart below in solving this problem. Enter all the information obtained from the clues by using an "X" to indicate a definite "no" and a "•" to show a definite "yes" for the corresponding cell in the chart. Remember: Once you enter a definite yes ("•"), place a no ("X") in the remaining cells in each row and column that contain the "•".

	Japanese Food	Italian Food	Greek Food	Fruits & Vegetables	Experimental Physicist	Hardware Designer	Data Analyst/Archivist	Data Analyst/Archivist	Travel	Classical Music	Mountaineering	Flying Airplanes
Dr. Cline												
Dr. Gehrels												
Dr. Hurley												
Dr. Kouveliotou												

7. The Power of These

Gamma Ray Bursts are the most powerful phenomena in the Universe! But what does that mean? Examine the bar graph on the poster. Can you see that the power is denoted using the number 10 and an exponent?



• Write out the power output of the light bulb and the power output of gamma-ray bursts in standard notation.

____

____

• How many light bulbs would you have to have to generate the same peak power as a gamma-ray burst? How many Suns would you need?

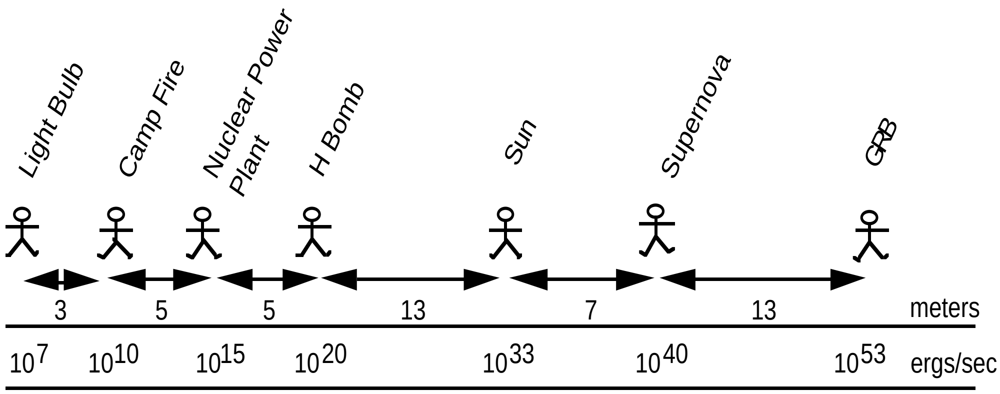
____

____

____

Let's try to visualize the great power of gamma-ray bursts!

Organize 7 people in a group. Have each of the seven people represent one of the different phenomena presented on the X-axis of the bar graph on the poster or the image above. All of the people should stand in a line; shoulder to shoulder, in order from least to greatest power. With the first person remaining in place, move one meter apart for every power of 10 difference between objects. See the illustration below.



• In the 7 person demonstration, the difference between the campfire and a nuclear power plant is how many meters? What is the difference in power between the campfire and the power plant?

____

How about between the H bomb and the Sun?

____

The nuclear power plant and the gamma-ray burst?

____

8. True or False

How well do you know the gamma-ray Universe and gamma-ray bursts? After reading the information in this booklet and after surfing the Web sites give in the Resource List, test your knowledge! Which of the following statements are true and which are false? Be prepared to defend your responses.

a. "If we could harness 1% of the energy emitted during a typical GRB, the Earth would have enough energy to last over 1,000,000,000,000,000 years, based on current usage statistics."

b. "Because of its enormous power, GRB 990123 posed a significant health threat to humans on Earth."

c. "The Earth emits gamma-rays that can be detected by orbiting satellites."

9. "About Once a Day"

Scientists will tell you that the BATSE experiment aboard the *Compton Gamma-Ray Observatory* detects "about one GRB per day". What exactly does that mean? Once you detect a burst, do you not have to look for another 24 hours in order to see the next one? That would certainly be easier and cheaper! Or does "about one burst per day" mean no such thing? Below is given small part of the BATSE GRB catalog which scientists use to analyze the frequency of GRBs. We selected 20 bursts detected during August 1996 from the catalog of over 7500 bursts.

A note about GRB names. Each burst is given a unique name. They contain a 6 digit number "yymmdd" for the two-digit year, two-digit month, and two-digit day of month of the burst occurrence. When more than one GRB is detected on the same calendar day, the suffixes A, B, C, etc are added after the yymmdd, usually depending on how bright each burst was relative to the other bursts of that day. So for example, 920503B refers to the second brightest burst detected on May 3, 1992.

Catalog Entry #	Burst Name	Secs of Day (UT)
5561	4B 960803	67522.445
5562	4B 960804B	70360.781
5563	4B 960804	84535.750
5564	4B 960805	77347.148
5565	4B 960806B	58713.289
5566	4B 960806	80909.773
5567	4B 960807	71366.344
5568	4B 960808	60123.848
5569	4B 960810B	24571.594
5570	4B 960810	83459.078
5571	4B 960812	50665.098
5572	4B 960813	20769.994
5573	4B 960813B	78438.086
5574	4B 960814	58847.945
5575	4B 960815	36027.082
5576	4B 960816	8167.242
5580	4B 960818	57760.457
5581	4B 960819	74182.344
5585	4B 960824	6110.921
5586	4B 960825	62837.578

• From these data, determine the mean, median, and mode of the data set which represents the time intervals between GRB detections.

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• What do these measures of central tendency tell us about the data?

____

____

• What is the maximum time interval between successive bursts?

____

• What is the minimum interval between successive bursts?

____

• What do all of these values tell you about how you must organize your observing program in order not to miss a burst?

____

____

____

Extension:

Get on the World Wide Web and download other sections of the BATSE GRB catalog (the 4th version of the catalog, which is the most current through July 1999) is available online at http://www.batse.msfc.nasa.gov/batse/grb/catalog/4b/4br_basic.html). Do you obtain the same results, no matter which section of the catalog list you take? Caution: be careful about using the most recent data...before verification, it can contain many false triggers, i.e. listings for bursts that never really happened!

V. Answers

1. Apparently, They are Absolutely Bright

1. The data are in the form of a power law.
2. Given an equation of the form $y=ax^b$, if a becomes larger, the distance between the curve and the x/y axes becomes larger. If a remains positive, but becomes smaller, the curve moves closer to the axes. If the absolute value of b becomes larger, the rate of change of the line is greater. If the absolute value of b becomes smaller, the rate of change of the line is smaller.
3. Knowing how bright something is does not really tell you anything quantitative about the energy emitted by the object. It may be bright because it is nearby, or it may truly bright. It may be dim because it is far away, or it may be truly dim. An astronomer needs to know something about the distance to the object in order to draw any conclusions.

2. It's Either Probable, or It's Not

1. No, the distribution of GRB locations in the sky is random.

4. 1/5

8. As you perform more and more trials, the theoretical and average experiment values will come closer together. Once you get over a thousand or so trials, the values will have essentially become equal and performing additional trials does not gain you much.

10. Given the random distribution in the sky, looking at a smaller part of the sky for a longer time will provide the same results as looking at the whole sky for a shorter time.

11. A instrument to observe a smaller field-of-view may itself be smaller. Thus it could be easier to construct, weight less so as to be easier to launch, cheaper to construct, and so on. A larger detector can see more at once, but it is more difficult and costly to make and launch such a device. However, the space environment is a harsh one in which an instrument must operate. So having an instrument provide as much data as possible in as short a time as possible is something to consider.

3. Blast from the Past

You may need to learn about units astronomers use to do this exercise. Here is a start, a parsec (pc) is equal to a distance of 3.26 light-years. Light travels at about 300,000 km/second.

Burst	Velocity (m/s)	Distance Away ($x10^6$ Mpc)
970508	$1.626x10^8$	2.17 – 2.71
971214	$2.707x10^8$	3.61 – 4.51
980703	$1.767x10^8$	2.36 – 2.95
990123	$2.227x10^8$	2.97 – 3.71

The two values given for distance are done based on the minimum and maximum Hubble constant values.

Taking the mid-range value of $3.3x10^6$ Mpc, or roughly 10 billion light-years, the light has been traveling for about 10 billion years. This tells us that the Universe is at least 10 billion years old. Based on the idea that GRBs originate with black holes, this tells us that 10 billion years ago, some type of stellar evolution must have already had time to take place. This could add a few billion years to the overall age of the Universe.

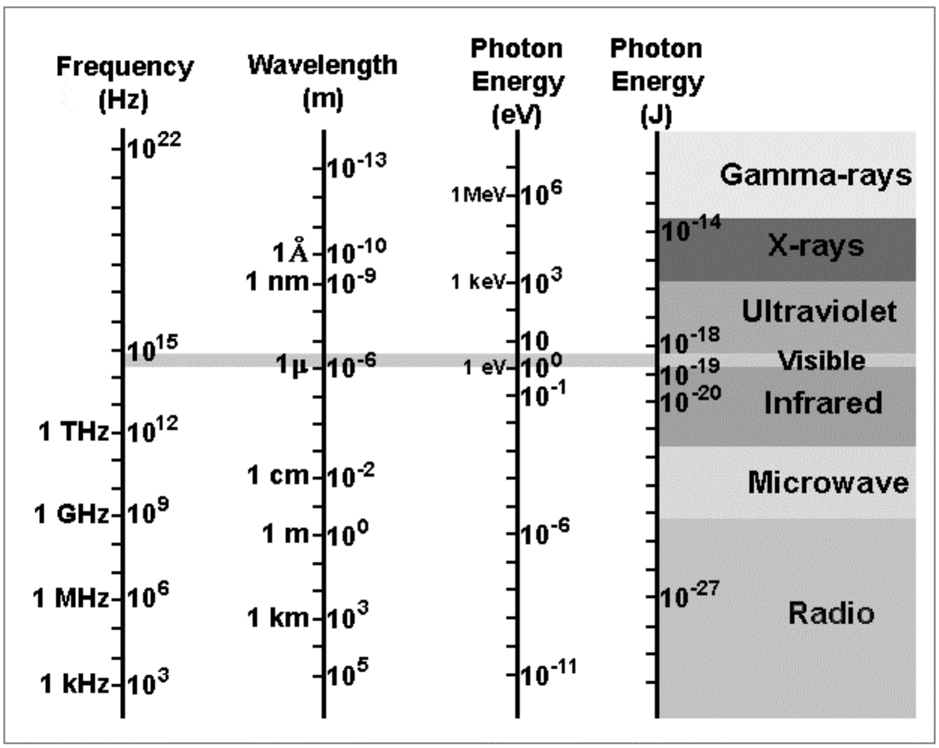
4. A Sensitive Situation

1. about 1 GRB/year
2. $10^{0.6} = 0.4$ photons/cm^2/second
3. ~ $10^{2.5} = 316$/year or ~ 6/week

5. When You're Hot, You're Hot…Unless You're Not!

Using Wein's Law, we find a temperature of 2.897×10^9 Kelvin. Be careful about your units! The core of the Sun is about 15,600,000 Kelvin. So, if the gamma-ray emission of a GRB is thermal in nature, the material would have to be over 100 times hotter than the core of the Sun.
It's hard to think of such a thing and, in fact, we are led to think that GRBs are not thermal in nature. Something else, some other physical phenomena, must be responsible for the gamma-ray emission of a GRB.

Below is a good reference chart for converting between frequency, wavelength, and energy (in two different units) for the various regions of the electromagnetic spectrum.



6. Behind the Gamma-Rays

	Japanese Food	Italian Food	Greek Food	Fruits & Vegetables	Experimental Physicist	Hardware Designer	Data Analyst/Archivist	Data Analyst/Archivist	Travel	Classical Music	Mountaineering	Flying Airplanes
Dr. Cline	x	x	x	•	•	x	x	x	x	x	x	•
Dr. Gehrels	•	x	x	x	x	•	x	x	x	x	•	x
Dr. Hurley	x	•	x	x	x	x	•	x	•	x	x	x
Dr. Kouveliotou	x	x	•	x	x	x	x	•	x	•	x	x

7. The Power of These

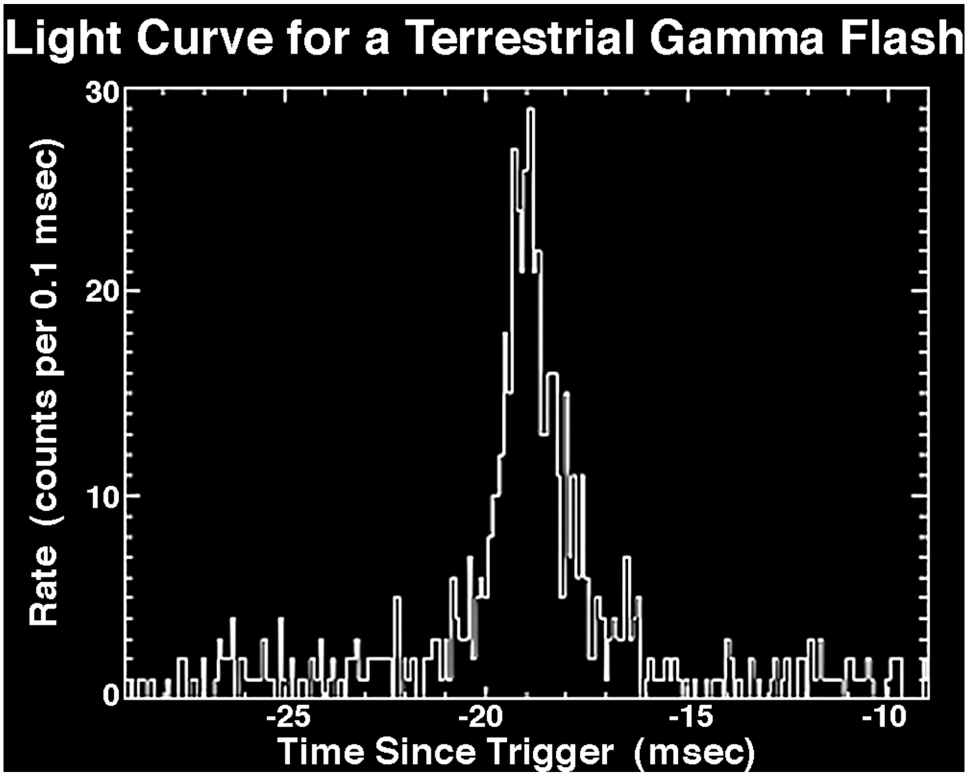
1. The light bulb would be 10,000,000 ergs/sec and the gamma-ray burst would be 100,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000 ergs/sec.
2. You would need 10^{46} light bulbs. You would need 10^{20} Suns!
3. The distance between the campfire and the nuclear power plant is 5 meters; this represents a difference in power of a factor of 10^{5} ergs/sec. The distance between the H bomb and the Sun is 13 meters; this represents a difference in power of a factor of 10^{13} ergs/sec. The distance between the nuclear power plant and a GRB is 38 meters; this represents a difference in peak power of a factor of 10^{38} erg/sec.

8. True or False

a. True. A single GRB at 1% efficiency could serve Earth's power needs for a hundred thousand billion billion (10^{23})years. GRBs can emit about 10^{54} ergs of energy. Worldwide energy use is approximately 10^{29} ergs/year.

b. False. Most GRB's, including 990123, GRBs originate very, very far away. The flux from them which reaches Earth is easily absorbed by the Earth's protective atmosphere. Only a GRB which occurs close by could pose a problem. Such GRB blasts are thought to occur rarely in our own Galaxy, perhaps once every million years. Researchers have estimated that an intense burst within 3,000 light-years of Earth could produce radiation at sea level equal to about 100 times the fatal dose for humans.

c. True. The graph below shows the time history of one of the events known as Terrestrial Gamma Flashes (TGFs). These events were discovered with BATSE to originate from high in the Earth's atmosphere, and are believed to be associated with large thunderstorm activity (Fishman, G. J. *et al*., 1994, *Science*, **264**, 1313).



9. About Once a Day

Using a quick method (just looking at the number of bursts per day and ignoring the time of day the burst occurred), you would get the following results:
Mean: 0.86 days
Median: 1 day
Mode: 1
If you do an exact calculation, converting the days and seconds of days into total seconds (remember a day has 86,400 seconds), you obtain the following:
Mean: 99795.501 seconds (1.15 days)
Median: 67765.539 seconds (0.784 days)
Mode: none

These measures tell us that there is a significant variation around the "once a day" value.
Maximum Time Interval: between GRB#s 5581 and 5585 is 363,928.577 seconds (~ 4.2 days)
Minimum Time Interval: between GRB#s 5562 and 5563 is 14174.969 seconds (0.164 days)

What you begin to understand is that you need to look all the time – because you just never really know when the next burst will occur!

VI. Glossary

Absolute Magnitude - apparent magnitude a star would have if placed at a distance of 10 parsecs from Earth

Afterglow - The electromagnetic radiation emitted after removal of a source of energy, especially: the glow of an incandescent material as it cools

Apparent Magnitude - a measure of observed light flux received from an object at the Earth

Arc Minutes - a unit of measurement used for very small angles; there are 60 arc minutes in one degree

Arc Seconds - a unit of measurement used for very small angles; there are 60 arc seconds in one arc minute

Black Hole - region in space where the escape velocity is equal to, or greater than, the speed of light. thus, nothing (including radiation) can escape from it

Cosmological – Related to cosmology, the study of the physical universe considered as a totality of phenomena in time and space. Cosmology is the astrophysical study of the history, structure, and constituent dynamics of the Universe.

Cosmological Distance – A distance that is a large fraction of the size of the observable universe.

Counterpart – An object which serves as the complement of another object or event. Related to GRBs, it is the object which astronomers can detect in other parts of the electromagnetic spectrum which is somehow related to the GRB. For example, the optical transient observed in the host galaxy of the GRB is the optical counterpart of the GRB.

Electromagnetic Radiation - radiation consisting of periodically varying electric and magnetic fields that vibrate perpendicular to each other and travel through space at the speed of light

Electromagnetic Spectrum - the full range of electromagnetic radiation spread out by wavelength, it consists of gamma-rays, X-rays, ultraviolet rays, optical light, infrared radiation, microwaves, and radio waves. Wavelength, energy, frequency, or temperature can classify these electromagnetic waves.

GRB – Gamma-Ray Burst

Hypernova – (**Hypernovae** is the plural) Possibly the most powerful explosions in our Universe since the Big Bang. Hypernovae are even more powerful than supernovae explosions, the spectacular bursts released at the deaths of massive stars. Still considered a hypothetical notion, a hypernova may emit 100 times more energy than a supernova, and represents a popular explanation for gamma-ray bursts. What causes a hypernova remains unknown, although astronomers have proposed that they happen when a very large and rapidly rotating star collapses. Another possibility is that the explosions aren't so bright after all, except for a pair of narrow flashlight-like beams of gamma-rays. The word "hypernova" was coined by Bohdan Paczynski, a professor of astrophysics at Princeton University in 1997.

km - kilometer = 0.6 mile.

Light-Year - the distance light travels in one Earth year, equal to 9.46×10^{12} km

Log-Log Plot - A log plot portrays each 10 to 1 change as a fixed linear displacement. A log-log plot does this on both the X and Y axes. Logarithmically scaled plots are extremely useful in science at showing two important aspects of a data set. First, the log plot expands the resolution of the data at the lower end of the scale to portray data that would be difficult to see on a linear plot. The log scale never reaches zero, so data points that are 1 millionth of the peak still receive equal treatment. On a linear plot, points near zero simply disappear. The second advantage of the log plot is that percentage difference is represented by the same linear displacement everywhere on the graph. On a linear plot, 0.09 is much closer to 0.10 than 9 is to 10, although both sets of numbers differ by exactly 10 percent. On a log plot, 0.09 and 0.10 are the same distance apart as 9 and 10, 900 and 1000, and even 90 billion and 100 billion. This makes it much easier to determine a spectral match on a log plot than a linear plot.

Luminosity - the rate of radiation of electromagnetic energy into space by a star or other object

Magnitude - The units used to describe brightness of astronomical objects. The smaller the numerical value, the brighter the object. The human eye can detect stars to 6th or 7th magnitude on a dark, clear night far from city lights; in suburbs or cities, stars may only be visible to mag 2 or 3 or 4, due to light pollution. The brightest star, Sirius, shines at visual magnitude -1.5. Jupiter can get about as bright as visual magnitude -3 and Venus as bright as -4. The full Moon is near magnitude -13, and the Sun near mag –26. The magnitude scale is logarithmic, with a difference of one magnitude corresponding to a change of about 2.5 times in brightness; a change of 5 magnitudes is defined as a change of exactly 100 times in brightness.

Neutron Star - the final stage of existence for stars born three to seven times more massive than our Sun. Neutron stars are produced by supernova explosions, which blow away most of the material of the star and leave behind a roughly 1.4 solar mass core. In these cores, material is so highly compressed that all the protons, electrons, and neutrons are piled together, breaking down the normal structure of an atom. These remnant cores are called neutron stars.

Parsec - unit of distance often used by astronomers, equal to 3.2616 light-years (a **kiloparsec** is equal to 1,000 parsecs)

Photon - a unit of electromagnetic energy associated with a specific wavelength or frequency

Progenitor – originator. Related to GRBs, the progenitor of the event is the object (or objects) which underwent some sort of catastrophic occurrence which resulted in the burst of gamma-ray emission.

Redshift - An increase in the wavelength of radiation emitted by a celestial body as a consequence of the Doppler effect.

Shockwave - 1. A large-amplitude compression wave, as that produced by an explosion or by supersonic motion of a body in a medium. 2. A violent disruption, disturbance, or reaction.

Speed of Light - the ultimate speed limit in the Universe: 300,000 kilometers/second.

Star - a self-luminous sphere of gas

Stellar Spectroscopy - breaking down the electromagnetic radiation from a star in order to study the different wavelengths individually

Supernova - (**Supernovae** is the plural) A supernova is one of Nature's grandest spectacles. Most commonly, it occurs when a star runs out of nuclear fuel. Its core collapses leaving the star's outer layers unsupported. They fall inward and the result is a gigantic explosion that for a day or so can outshine all the stars in a galaxy.

Universal Time (UT, or UTC) - A measure of time used by astronomers; UT conforms (within a close approximation) to the mean daily (apparent) motion of the sun. UT is determined from observations of the diurnal (daily) motions of the stars for an observer on the earth. UT is usually used for astronomical observations, while Terrestrial Dynamical Time (TDT, or simply TT) is used in orbital and ephemeris computations that involve geocentric computations. Coordinated Universal Time (UTC) is that used for broadcast time signals (available via shortwave radio, for example), and it is within a second of UT.

VII. About the Poster

One of the most amazing things about gamma-ray bursts is their enormous power. Power is defined as the amount of energy emitted per unit time. Shown on the poster is a bar graph which compares the power emitted by several different radiant objects or events. The values given represent the peak power output of each. In other words, it is a snapshot in time at the instant each object or event is emitting the greatest amount of power it will ever emit. Some things – like the light bulb – emit constant power over time. Other things like a supernova explosion or a gamma-ray burst can emit enormous amounts of power one second and thousands or hundreds of thousands of times less power the next second. By showing peak power, we allow ourselves to compare very different things like light bulbs and supernovae in a meaningful way. Simply put, we display on our graph the following information: in the one second (whenever it occurred) that they each emitted their maximum power, what was it?

It may be interesting to consider the total energy (or power x time) emitted as well. This takes into account the amount of time that each object or event emitted energy and how much energy they emitted as a function of time. Consider this, the total energy emitted by a supernova is only about a factor of 10 to 1000 less than that emitted by a gamma-ray burst. Given the values you see on the peak power graph on the poster, what does this tell us about the amounts of time over which these events occur?

Running down the left side of the poster is a series of images which illustrate how the light curve of a GRB (i.e., a plot of its intensity as a function of time) would appear as an image on the sky. While based on real data, these images are only meant to be illustrative; you cannot, in fact, create an all-sky image in gamma-rays on the brief timescales of a GRB. What the illustration shows is that a burst can become so bright that it overwelms the elements of the detector which are imaging the burst location. Those detector elements become overloaded and begin to "spill over" into the nearby detector elements. So in a way, the size of a spot on the image is proportional to the intensity of the source (of course, so is the color of the spot). What you will notice is that at the maximum of the GRB, the event is brighter than the whole rest of the sky and temporarily blinds the detector to seeing anything else.

VIII. Related Resources

Web sites

Swift Mission - http://swift.gsfc.nasa.gov/

Glast Mission - http://www-glast.sonoma.edu/

Compton Gamma-Ray Observatory - http://cossc.gsfc.nasa.gov/cossc/PR.html

Cosmic Gamma Ray Bursts - http://www.batse.com/

Imagine the Universe! – http://imagine.gsfc.nasa.gov

Magazines

• Paczynski, B. 1998. Are gamma-ray bursts in star-forming regions? Astrophysical Journal Letters 494(February 10):L45.

• Cowen, R. 1997. Gamma-ray burst mystery continues. Science News 151(May 17):305.

• Cowen, R. Gamma-Ray Burst Makes Quite a Bang, Science News, Vol. 153, No. 19, May 9, 1998, p. 292. Also available on the Web at http://www.sciencenews.org/sn_arc98/5_9_98/fob1.htm

• Cowen, R. The Dark Side of Gamma-ray Bursts, Science News, Volume 156, Number 2 (July 10, 1999), cover story

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