UATP: X-RAY VIEWS OF THE PHYSICS OF THE UNIVERSE

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I teach a class each summer for the graduate students at Columbia which among other things tells them how to give a talk. And contrary to the advice which people usually get which is "never underestimate your audience; use all those big words; make sure you throw in all the references to the right famous people," my advice is never to overestimate your audience.

And this comes about because of a incident that occurred to me about twenty years ago. The physics department at Columbia used to have its colloquia at 11:00 o'clock on Friday morning, and then everyone would go to the traditional Chinese lunch. And so we had a talk by an astronomer at one of these colloquia, and he was talking a lot about massive stars. And as I walking to lunch with one of my senior colleagues, a very well known but shall remain unnamed particle physicist, he said: "Well, this guy was talking about massive stars. But you don't really know the mass of a star; you're just talking about bright stars or something; you really shouldn't call them massive." And I said, "No, we actually know the masses of stars." And he said, "How can you know the masses of stars?" And I said, "Well, you know, because they orbit around each other and there are these laws of motion that Newton came up with." And he goes, "Really? You can actually measure the mass of a star?"

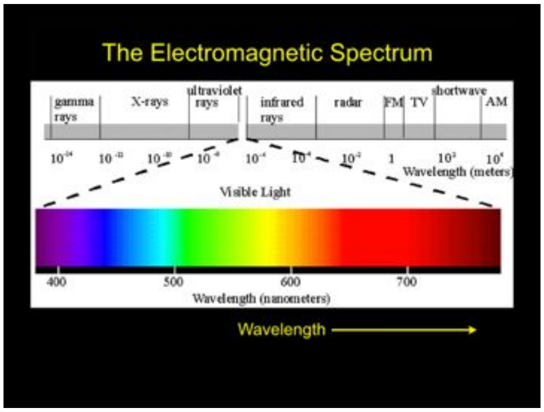


FIGURE 1. Your eye sees only 1 octave

I'm going to suggest a slight redefinition of the title of this meeting. Maybe it's "Using Astronomy to Teach Physicists." So don't take offense if I'm speaking below you. But what I'm going to try to do is give you some interesting ways to introduce some of these concepts. And even if you know them, hearing them is worthwhile if they're interesting in new ways.

So I always start my talks on the x-ray universe by talking about how terrible your eye is as a tool to measure the universe. I mean your eye sees precisely one octave of radiation from about 380 to 760 nm. The universe sends us 50 octaves of radiation, and you see 1; you see 2% of the total (Fig. 1). And all the telescopes built from 1610 until 1950 something only saw this 1 octave of the universe. I mean, imagine! Your ear hears 10 octaves of music, so rather than slicing off this tiny bit of the spectrum, your ear hears at least 10 octaves of the spectrum. Imagine how terrible it would be to listen to music if your ear only heard a single octave.

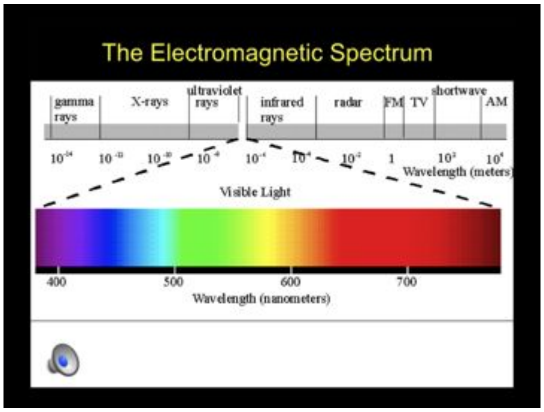
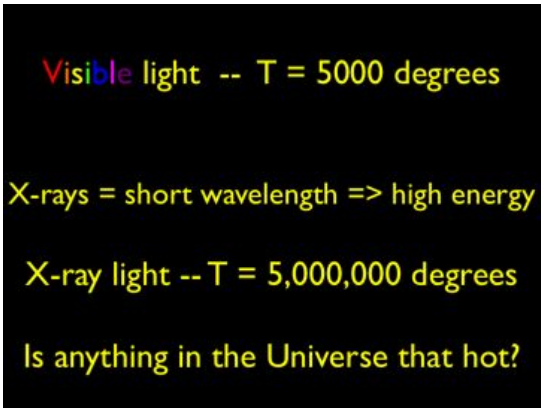

The Electromagnetic Spectrum

Figure 2. “Ode to Joy” in only one octave loses its essence.


Visible light -- T = 5000 degrees

X-rays = short wavelength => high energy

X-ray light -- T = 5,000,000 degrees

Is anything in the Universe that hot?

Figure 3. For 60 years astronomy has been opening 49 more octaves

Well, you don’t have to imagine that because I found a clever graduate student at Columbia in the music department. And so I took the “Ode to Joy” and I did to the music what your eye does to the universe I sliced it up one octave at a time. [plays music] So here you have the glory of the orchestra, the piccolos over the sound of the double basses. But now let me put a filter on that gives you 1 octave around the 440 A. [plays] I mean from the rhythm you can sort of tell what it is, but it’s not really very attractive. And then let’s take another random octave. [plays] And now this probably won’t even work with these speakers [plays some very low sounds]. That’s another octave – a random tiny piece of this music that you want to hear. [harsh hissing sound] Hard to recognize that. And here’s one a few octaves higher; this would be the equivalent of the x-ray part of the spectrum; it sounds like a bunch of angry crickets. It’s only when your ear and your brain integrate these into this glorious whole, this whole ten octaves, that you get the experience of the music introduced. [plays Ode to end]

So what astronomy has been about for the past 60 years has been opening up the other 49 octaves so that we can see the entire variegated picture that the universe presents to us. Now in visible light — what the colors represent in Fig. 2 — we see things that are at a temperature of about 5000 K. That’s not an accident. We grew up on a planet that revolves around a star that’s at about 5000 degrees so naturally our radiation detectors were tuned to 5000 degrees. X-rays, of course, are much shorter wavelength and much higher energies, and x-ray light is characteristic of a blackbody spectrum – we’ll peek at the spectrum and see what that is. It comes out around 5 million degrees. So the question naturally would be: If you never looked at the x-ray sky before, which was the case in my lifetime, “Is there anything in the universe hot enough to produce x-rays?”

Well, so Fig. 4 shows what the Sun looks like if you have binoculars with solar filters. It’s pretty boring. What you’re seeing is where the surface of the Sun is — it’s not of course a solid surface but what you’re seeing is the surface that emits the kind of

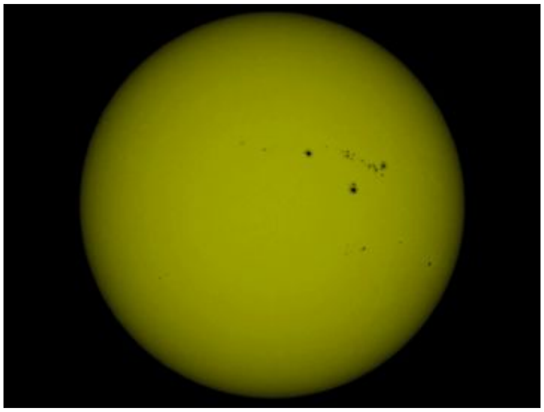


FIGURE 4. A boring view of the Sun

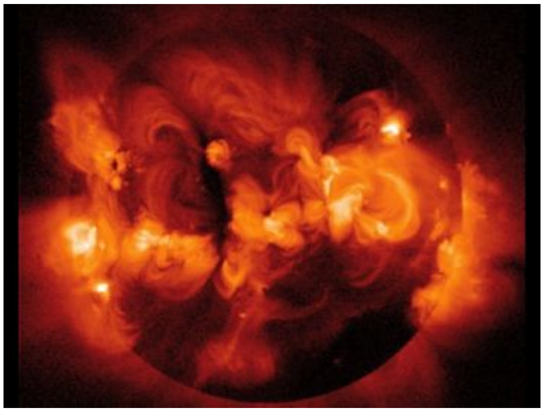


FIGURE 5. X-ray picture of the Sun

light your eye is tuned to detect. So you're seeing the surface at 5800 degrees, and if you put that into $\lambda_{\max} = .0029/T$ m, it's 500 nm which turns out, not surprisingly, to be the peak of the sensitivity of your eyes.

You can also notice though, which you can't see with your naked eye, a few little black splotches on the image. So what does black mean? Black is the absence of light. Right? And therefore, those pieces of the Sun aren't emitting light so maybe they are a lot cooler. But it turns out that when you look at the Sun, with an x-ray telescope which, of course, you had to go above the atmosphere to do because, you would say, photoelectric absorption of the atoms in the atmosphere doesn't allow the x-rays to penetrate to the ground – the Sun looks somewhat more interesting.

Figure 5 is an x-ray picture of the Sun, and those little black dots turn out to be the brightest places here, because this is where the gas has temperatures of 10 (and even higher) million degrees. And there are black regions in this part of the picture as well, and that is where there is no gas with temperatures of millions degrees, and, as a consequence, the Sun is not emitting at x-ray wavelengths.

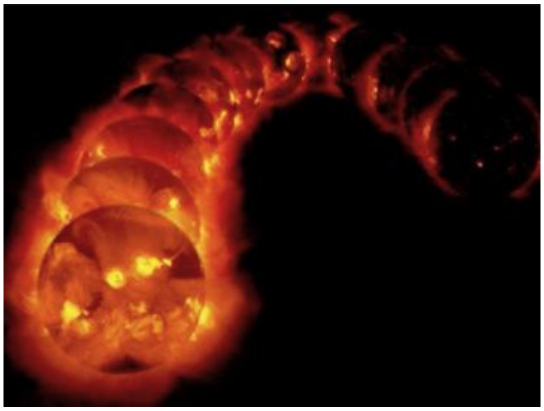


FIGURE 6. Montage of Suns over 5 years — from solar max to near solar minimum.

You see the picture is remarkably different. It's as different as the first octave I sliced out of the "Ode to Joy" and the second octave I sliced out of the "Ode to Joy," and, therefore, clearly opening these windows allows us to give a much richer picture of what the Universe is like.

FIGURE 7. The first solar x-rays were seen with sounding rockets.

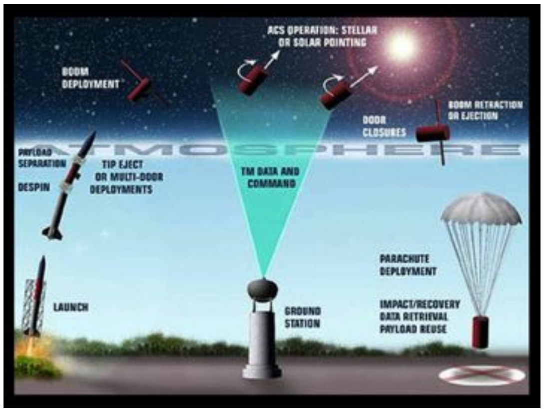
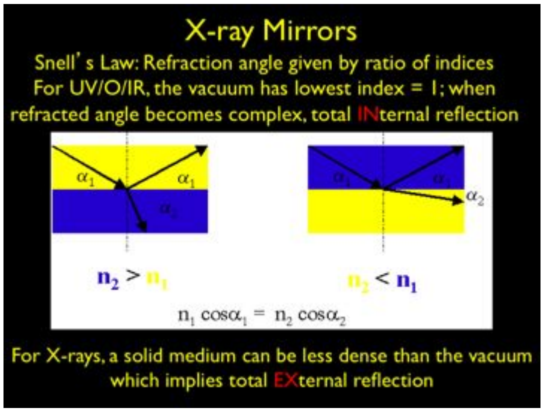


FIGURE 8. How sounding rockets work today.

Now if you want to teach physical principles about this, there is also a lesson about the history of the Sun over 11 years. The Sun, of course, varies in its activity, and the number of Sun spots on its surface ranges from about zero, as we had a few years ago, to as many as a couple of hundred at a time. And, therefore, the amount of activity in these fundamentally magnetic events iprovides huge amounts of physics to talk about – things we never talk about in E&M like magnetic reconnection, when north and south poles connect together, releasing enormous amounts of energy and heating the plasma to high temperatures and powering the corona of the Sun, this lovely halo around it.

So how do we do these things? We need first of all to get above the atmosphere here. So the first thing you can actually put into a standard introductory physics class is . . . rockets! Right? Rockets go up, and they come down. The first x-rays were detected in space by modified V-2 rockets that were captured after World War II. A little piece of film put in a canister, send it up and let it fall down – a perfect parabola just like that — and they detected x-rays from the Sun. As Fig. 8 shows, we now have somewhat more sophisticated ways of doing this, but nonetheless that's some physics you can put in. And you can put in all kinds of fancy stuff about how the rocket is spinning. It needs to be spun up to be stabilized, and it has to despin again. And you can even have them calculate the probability of the instrument you've worked on for five years as a graduate student coming down in a lake or a tree, or something like that. So, lots of things to do there.

Of course, a piece of film in the nose cone of a rocket doesn't give you the spectacular picture of the Sun with arc-second resolution that you see in Fig. 5. So how do they actually do this? With mirrors. But how do you make an x-ray mirror? Well, you say, you just make a mirror and the x-rays bounce off. Well, what is the spacing between atoms? Well, it's a few Ångstroms. Well, what is the wavelength of an x-ray? Well, it's a few Ångstroms. So, what does an x-ray do? Well, what does it do to your cheek when you visit the dentist's office? It



X-ray Mirrors

Snell's Law: Refraction angle given by ratio of indices
For UV/O/IR, the vacuum has lowest index = 1; when refracted angle becomes complex, total INternal reflection

$n_2 > n_1$ $n_2 < n_1$

$n_1 \cos\alpha_1 = n_2 \cos\alpha_2$

For X-rays, a solid medium can be less dense than the vacuum which implies total EXternal reflection

FIGURE 9. X-rays and total external reflection

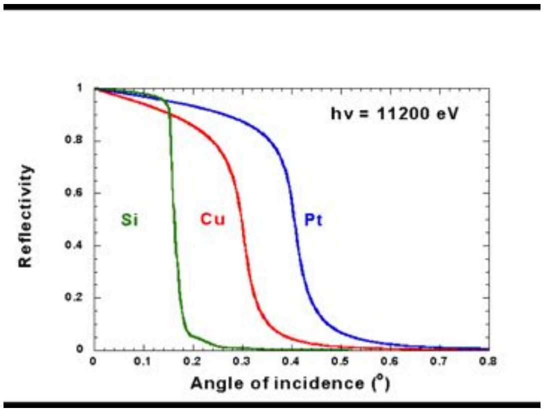
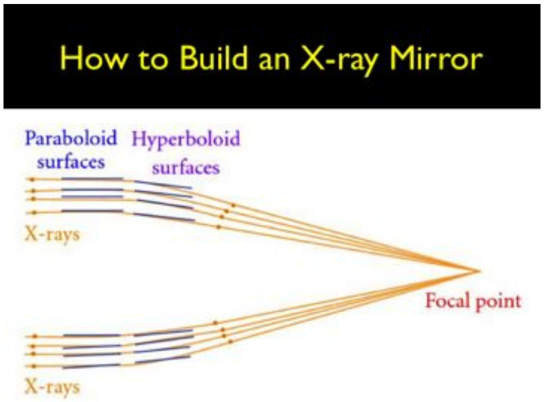


FIGURE 10. Grazing angle reflectivities of Si, Cu, and Pt



How to Build an X-ray Mirror

FIGURE 11. Nested paraboloid surfaces focus x-rays.

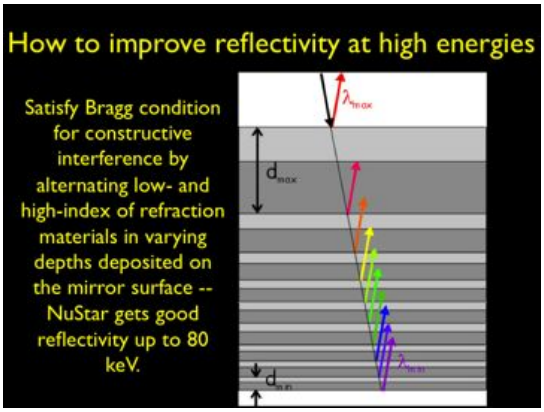
goes right through. So you don't make normal incidence mirrors.

You take advantage of what's called total external reflection. In an optics class, in the first couple of years anyway, you might talk about the total internal reflection when you set something up so that the index of refraction is such that the refraction angle goes imaginary, and you get total internal reflection. And that's true for the optical and the infrared and the ultraviolet part of the spectrum because the vacuum has an index of refraction of 1, and anything else has a higher index of refraction so it's possible to have total internal reflection. But for solid materials and the x-ray part of the spectrum, a few keV or so, then in fact a solid's n can be less than the vacuum's, and so you get total external reflection. We take advantage of that to make x-ray mirrors. Now the grazing angles have to be very small, and you can see from Fig. 10 how small they have to be, and, of course, they're a function of the materials – the silicon, copper, platinum here. The angle of incidence from which you get total external reflection is about .1 to .3°. That's a really small angle, and the consequence is that surface area on an x-ray mirror is not πR^2 as it is for a normal incidence optical mirror. Here you are looking at it an angle of 0.3°, and so you're making a few 100 cm^2 out of a mirror that's half the size of this room, ... which makes x-ray mirrors expensive. But that's what we have NASA for... or at least, that's what we used to have NASA for.

So how do you build x-ray mirrors? Well you want to focus them to a point; you want to do this right. And there are several geometries that are possible – and this is something else that's interesting to explore that you never see in an optics class. Most of the x-ray telescopes that have been launched are this model shown in Fig. 11 or an approximation of this model – a paraboloid surface where you get a thing that is shaped like a parabola followed by a hyperbola and those two focus x-rays to a point. And in the Chandra observatory it focuses to a point with a spot size of less than 0.5 arcsec. And so you can get images that are comparable to optical images from the ground if you're willing to spend – what was it, Roger? – a billion dollars or something like that on these mirrors with a total effective area of a few hundred square centimeters.

Notice that at 11 keV those angles had to be very shallow, and as you go up in energy, the angles get shallower and shallower, so you have a real problem if you want to take pictures of the sky at x-rays that the dentist uses on your mouth, you know, 30 or 40 keV say. And in fact, the only window of the 50 octaves of the spectrum that I showed you in which we have not had a telescope flying above the Earth or observing from the ground with true focusing optics is the 10 to 100 keV band.

And, by the way, Roger and I both just came from a meeting at Caltech on discussing the pre-launch science that we're going to do with the satellite of this type that's going to be launched on February 3rd, if everything goes smoothly, of next year, where we are actually focusing x-rays at these very high energies. The technique (Fig. 12) is very clever, and there's lots of interesting physics in it.



How to improve reflectivity at high energies

Satisfy Bragg condition for constructive interference by alternating low- and high-index of refraction materials in varying depths deposited on the mirror surface -- NuStar gets good reflectivity up to 80 keV.

Figure 12. Graded mirror gives better reflectivity of 10 – 80 keV x-rays

If you have something come in that satisfies the Bragg condition, hit the layer of higher density material, and reflect off and interfere in phase with the x-rays bounced off the surface, you can amplify the amount of reflection. And so for one of these disks for a range of energy we make what is called a graded mirror where we deposit layers of various thicknesses going down which reflect wavelengths as they get smaller and smaller of higher and higher energy. (See Fig. 12.) And you can reflect a whole spectrum of x-rays, in our case from about 5 keV to about 80 keV by changing the thickness the layers and changing the Bragg condition and changing the constructive interference. And so you can channel a whole range of x-rays over a whole broad band by playing with the surface of the mirrors. All kinds of effects come into play in your old mirrors that you had in your second year optics course or played with in lab.

Now, what do we see when we make mirrors like this? Well, we see lots of things, and lots of interesting physics has come into play. Here's a picture of the Moon in x-rays. Now you probably don't think of the Moon as an x-ray source, because, after all, the Moon's not at 5 million degrees. It's considerably colder than that. But the Sun, as you see,

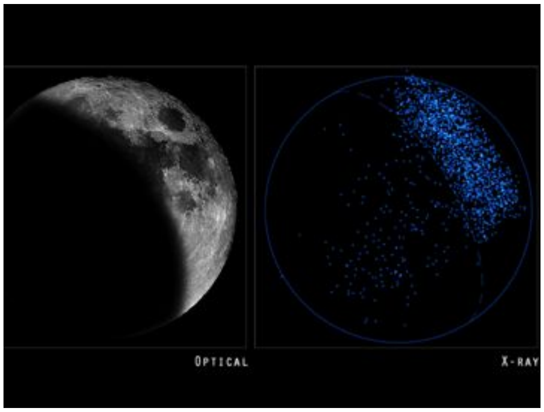


FIGURE 13. X-rays from the Moon.

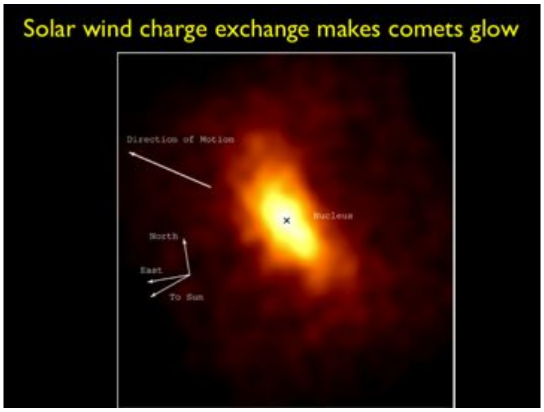


FIGURE 14. X-rays from a comet?!

produces lots of x-rays, and we know you can see the Moon in optical light because of the light reflected from the Sun. Figure 13 shows two images of the Moon, one in reflected sunlight, the other in x-rays. There are lots of x-rays from the part being struck by sunlight — that's silicon, aluminum, and magnesium fluorescing as x-rays and particles from the Sun hit the surface of the Moon and produce x-ray fluorescence and x-rays where the Sun is shining on the Moon.

But the disturbing part of this picture when it was taken is that there are also x-rays from the dark side of the Moon. So what's going on here? There are no solar particles or x-rays hitting that part of the Moon. And it turns out that those are not from the Moon. Those are a very interesting phenomenon which is also the reason why some of the coldest things in the Universe – like comets – glow brightly in x-rays.

Comets are big frozen snowballs, and here (Fig. 14) is an x-ray picture of a comet. So what's going on here? What is going on in both cases is that you have a charge exchange reaction from carbon, nitrogen, oxygen – things like that – coming from the Sun, high energy particles, slamming into hydrogen atoms that are in the geocorona of the Earth, just floating around out there in escape from the Earth because you know hydrogen is too light to be held by the gravitational capture of the Earth so hydrogen atoms are constantly leaving the Earth as water is dissociated by lightning and things like that, and these high energy particles from the Sun slam into them and steal the electrons from the hydrogen atoms and then the electrons cascade down and generate a bunch of x-rays. And so these x-rays don't really come from the dark side of the Moon, but from atoms 10,000 km up in the Earth's atmosphere that are undergoing these charge exchange reactions with high energy solar particles. And comets, which are subliming lots of ice as they come closer and closer to the Sun, provide a nice thick target for all these high energy ions from the Sun to undergo these charge exchange reactions and then they glow.

This is the classic example of sort of serendipity or somebody having a crazy idea. We didn't know that comets did this. It hadn't occurred to anybody. The physics is pretty obvious, but it hadn't occurred to anybody.

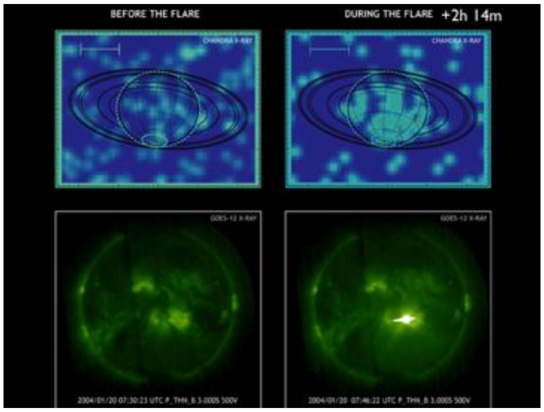


FIGURE 15. Saturn's x-rays produced by the Sun

FIGURE 16. Stars forming in the Carina Nebula

And the Germans put up Rosat about 20 years ago, and then someone on a whim decided to look at a comet. It seemed like a crazy idea. Comets are frozen, right? So why would you see x-rays? And that's how this was discovered.

Figure 15 is another cute picture taken by the Chandra observatory of the planet Saturn. In the upper part you have Saturn; in the bottom part you have the Sun. Saturn, of course, is pretty cold, so it doesn't emit x-rays. Well, the Sun when it has a solar flare releases a huge burst of x-rays, and observing Saturn 2 h 14 min after this 10-minute long solar flare, the whole disk of Saturn lit up. 2 h 14 min is the light travel time from the Sun to Saturn and back to Earth. And there you see the whole planet lighting up. And you may say, "Well, that's cute. But so what?"

Well, as we launch more and more spacecraft into farther and farther orbits from the Earth, we're interested in space weather. We are interested in space weather in general. And you can see, of course, solar flares and corona mass ejection and all these things that happen on the side of the Sun facing us, but we can't see the other side. But the planets Jupiter and Saturn are often on the other side of the Sun, so we can just monitor them, and we can see what's going on that side of the Sun as well . . . and map the space weather of the entire Solar System.

Okay that's all Solar system stuff. Most of us are astronomers who don't consider the Solar System astronomy, so let's talk about other stars. And the Sun is a very typical star in many ways, so we shouldn't be surprised to learn the other stars produce x-rays as well. And, in fact, many stars, particularly early in their lives when they are forming in regions like those shown in Figs. 16 and 17, produce lots of x-rays. And this has interesting implications for the history of the Earth. Because of pictures from regions like this, it is thought that when the Sun was young, it produced a lot of x-rays.

Now Fig. 18 is one of the iconic pictures in the Hubble Space Telescope in that pathetic little piece of the spectrum that our eyes can see. And we see these three pillars of gas, dark, not because they're not emitting light but because they're full of small dust particles that are blocking the light from behind.

FIGURE 17. Detail of x-ray activity of star forming region of Carina Nebula

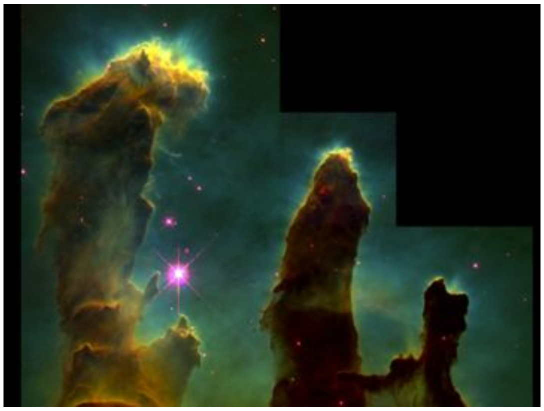


FIGURE 18. Pillars of Creation in M16 Eagle Nebula

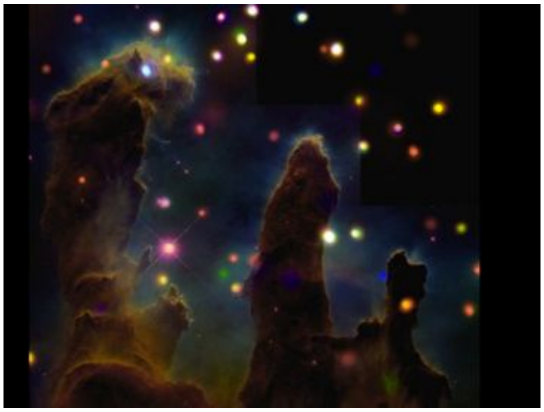


FIGURE 19. X-ray view of Pillars of Creation

And in these regions where we expect stars to form, these little fingers are a few times the size of the Solar System, and they represent regions of the gas that started rotating sufficiently that it spun out into a pancake that's started to form a star at its center with planets around it. So there are dozens, if not hundreds, of stars being formed here. But with visible light, because these little particles of dust are such that they scatter the light coming from objects that hid it, buried inside, you can't see inside. You can't see inside with visible light. But with x-rays you can.

Focus on the top of the leftmost pillar. This is an x-ray picture of that same region superposed on the optical image, and you see at the top there's this bluish, bright object glowing which you didn't see at all on the other picture. – wasn't there at all – and that's because it's a bright, young star which is glowing in x-rays, and the x-rays are sufficient to penetrate the dust. So you can x-ray the cloud like you can x-ray your teeth and see what's going on inside. And the color here is not random; the colors are assigned as they are in visible light such that the lowest energy x-rays are red and the highest energy x-rays are blue. So this blue light thing out there is very hot, whereas some of these other red ones down here, which are in regions where there is no dust obscuration so the x-rays can come to you directly, are at somewhat lower temperature; they are lower energy x-ray objects.

These star formation regions turn out to be very rich sources of x-ray emitters. In Fig. 20 we have an optical picture sort of in

FIGURE 20. RCW 108 region of star formation only 1.3 kpc from Earth

FIGURE 21. NGC 3603 starburst region

the red and yellow, and the blue are x-ray sources. You see they're everywhere. You can't see stars underneath them in lots of these dusty regions because again the dust blocks the visible light plus they are all over the place. And as these star formation regions grow, as the stars turn on, they have very strong stellar winds, (Fig. 21 is just a different optical picture) and blow away the cocoon of dust out of which they formed and you end up with a cluster of stars. Figure 22 shows a dramatic x-ray picture taken by Chandra. The background in white and yellow is an optical picture, but within the white outline everything in red is an x-ray picture. And you can see literally there are 1500 stars in here that have formed in this cluster, some of which you can see optically, some of which are still buried in their nascent cocoon so you can't see them optically, and they shine through. You can see that the big bubble there was blown when most of the gas went to all of them, whereas lower down in the outline you can see fewer of them. That's because a lot of the gas is there, sufficient gas to block the x-rays as well.

FIGURE 22. Composite optical and x-ray view of stars forming in the Rosette Nebula

So that's the beginning of stars' lives; at the end of stars' lives they tend to emit x-rays as well. Figure 23 is a globular cluster, a very old star system, gravitationally bound, a hundred thousand stars or so. And most of these stars, because the cluster is old, are less than the mass of the Sun, so they're also old, by definition, and as a consequence they've lost a lot of their angular momentum. The angular momentum is

FIGURE 23. NGC 6093 globular cluster about 10 kpc from Earth.

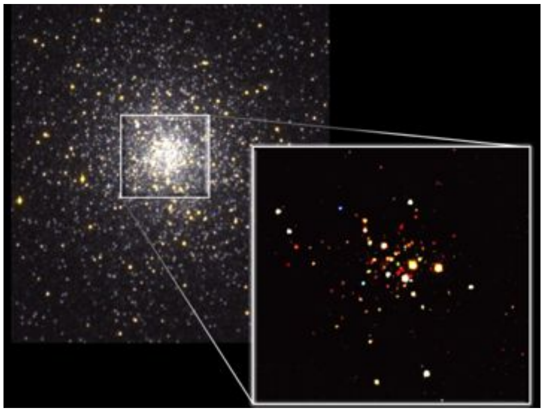


FIGURE 24. Optical view of the globular cluster NGC 104 (47 Tucanae) with an x-ray image of its core.

FIGURE 25. Cats eye nebula shows shells from successive ejections of matter by a star nearing the end of its life.

what drives the generation of magnetic fields which drives the solar coronal activity, and so we expect these stars not to be very bright x-ray sources. But when we look with an x-ray telescope at the core of this cluster, where the density of stars is enormous, we see in fact there are lots of x-ray sources, more than a hundred x-ray sources, in the center of this cluster. And these represent the consequence of this kind of location in the galaxy. It doesn't happen anywhere else. It happens where the stars are so close together that they have lots of gravitational interactions. If the star density is sufficiently high, while they are extremely unlikely to actually collide head on, they're likely to interact sufficiently that they get captured into binary systems, that you have two stars orbiting around each other. Then a third one comes in, steals some of the energy and makes the binary tighter – or harder, as we say – and as a consequence leads to the transfer of matter from one star to another. A lot of these stars are neutron stars and white dwarfs, the remnants of normal stars which have been captured into orbits around ordinary stars and are stealing matter from them. As the matter falls down the gravitational potential well, it heats up – you know, mgh; you can get a lot of energy out that way – and if it falls into a deep enough gravitational potential well, you can get x-rays out.

The end of the life of an old star, our Sun for example, will be when it runs out of nuclear fuel at the center. It's burned all the helium into carbon; it doesn't have sufficient overlying pressure to squeeze the carbon tight enough to burn carbon into oxygen and neon; and in consequence it will undergo an unstable period where it stopped nuclear burning, and so the star swells up a little bit. But that releases the pressure — and you can do all these arguments about balance of pressure and temperature. Then the nuclear reaction turns off, so the star starts to contract again, because there's no energy flowing out of the center, and gravity is still there. But then, of course, the density and temperature get high enough to turn the nuclear reaction on again so it expands again, and it gets into an unstable oscillation mode where it blows off dozens of radiative materials over a hundred thousand years or so until it has lost maybe half its mass. (Fig. 25) There's lots of interesting physics in that. So these clouds of gas are heated by the star; the stars are at 10,000 degrees, and so you expect the gas to remain visible in ultra-violet light. However, it turns out that these shells as they overtake each other produce shock waves – lots of fluid mechanics in astrophysics – and then what we see in Fig. 26 is that some of these regions can get to very high temperatures. The red picture is their gas in the visible light, while the blue is x-rays, which come from regions heated to millions of degrees. You see the hot x-rays filling in where the gas has been shocked to high temperatures.

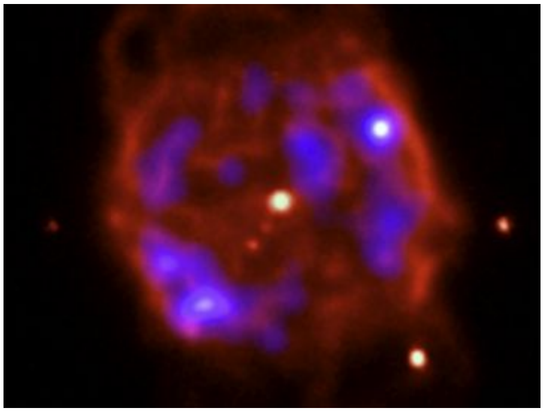


FIGURE 26. Blue areas show where x-rays are produced in shock waves.

The most dramatic example of the end of a star, of course, occurs for massive stars which manage to get beyond the point the Sun will and can easily turn carbon into oxygen and neon and then can turn neon into magnesium and silicon and then can turn silicon into iron and synthesize all the elements. So, nucleosynthesis – where did the elements come from, an obviously interesting question which most first year physics students haven't thought about, and an interesting way to introduce the topic that elements apart from hydrogen and helium and a tiny trace of lithium all came from the stars, and they came building up in a series of nuclear reactions starting with the fusion of hydrogen and helium all the way up to iron, which, you will point out to your students, is the minimum in the nuclear binding energy curve such that it is the most stable arrangement of protons and neutrons such that if you take away another proton or a neutron from an iron-56 nucleus, then you're going to take away energy – it's going to be an endothermic reaction; and if you add another proton or neutron to an iron 56 nucleus, it's going to be an endothermic reaction.

So while throughout the star's life the gravitational force trying to crush the star has been balanced by the nuclear reactions in the center pushing energy out of the star,

FIGURE 27. Cas A in the visible

FIGURE 28. Composite of Cas A viewed in x-ray and optical light.

all of a sudden in the final five days of its life a 20 solar mass star turns a solar mass's worth of silicon into a solar mass's worth of iron and then tries to make cobalt and nickel and that, of course, sucks energy out of the center of the star only half a second before it collapses. That releases a lot of gravitational energy, about 300 times the Sun's 10 billion year nuclear energy source in half a second, and a lot of energy in a given place and a given moment in time is called an explosion. And so the star blows up.

Now the point is that the star blows up with such violence that the typical velocities of the material flying off into the interstellar medium is 5 to 10 and even 30 thousand kilometers a second. And if we calculate the temperature of a shock at 10,000 km/s, it's not going to give you a lot of visible light. Figure 27 is a very deep optical image with the Hubble Space Telescope of one of the more recent of these explosions in our Galaxy – Cas A. But Fig. 28 shows what it looks like in x-rays – a little more impressive, because most of the gas is at 5 to 20 million degrees. And, yes, the colors are meaningful. The blue colors are the highest energy x-rays; the red colors the lowest energy x-rays. You notice there's sort of a shell of very high energy x-rays going around the outside and, since it's a sphere in three dimensions, probably part of the front as well, where inside, the gas is moving slowly as you might expect as a shock wave accelerates down the density gradient from the center of a star to the rarified outer regions of the star. It turns out this outer radiation may be here for a different reason as well.

But you can take pictures of this remnant in single nuclear lines of the elements. So in the upper left iof Fig. 29 is the total picture; there's silicon; there's calcium; there's iron. And you can see directly the freshly synthesized material this star has produced. There's tens of thousands of times more calcium and iron in this much gas as you would find in a standard interstellar cloud. It has all been produced inside the star and regurgitated into the interstellar medium where it will enrich the material that forms the next generation of stars.

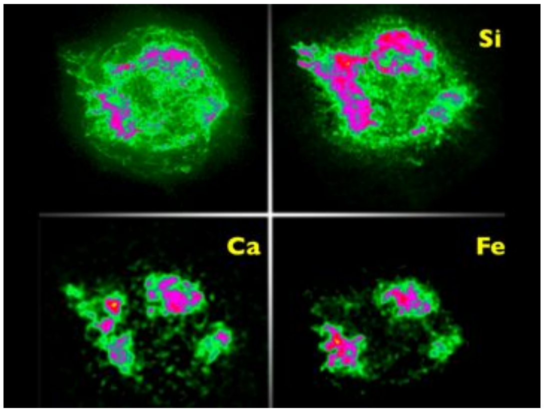


Figure 29. Supernova remnant viewed in wavelengths emitted by three different elements

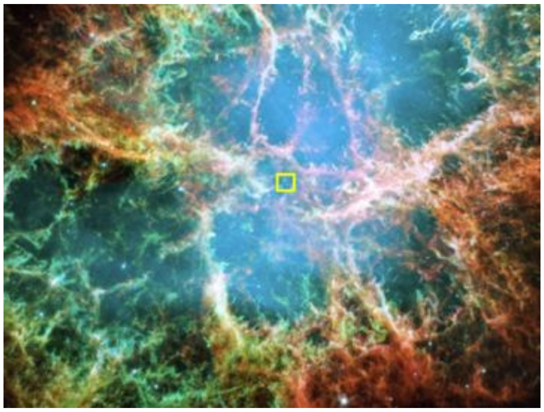


Figure 30. Crab Nebula photographed by the Hubble Space Telescope.

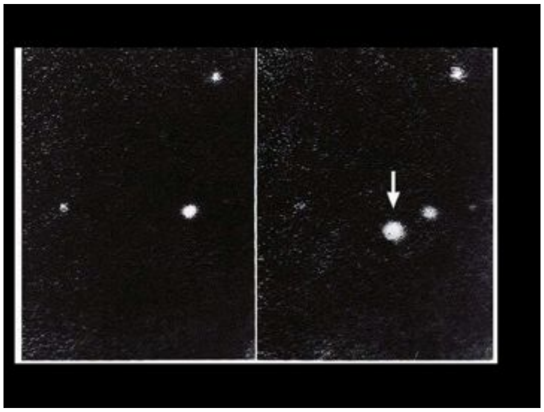


Figure 31. Pulsar at the center of the Crab Nebula

This is pretty convincing that you see this here, but even more convincing would be seeing freshly synthesized radioactive material that has a short half-life. And that's one thing the satellite I mentioned – it's called NuStar and will be launched next February — will do. It will look for lines from freshly synthesized titanium-44 generated in supernova remnants. Because it has a short half life and will die within a few thousand years, we can look through the Galaxy and find all the recent explosions and look at them and measure in quantitative detail how much of this isotope is produced and use that to feed back on models of these events.

The other things that supernovae produce are two of the more extreme forms of matter in the Universe neutron stars and black holes. Figure 30 is an optical picture of what, until about 10 years ago, I guess, was called the most studied object in astronomy – the Crab Nebula. It's a glowing cloud of gas and dust which in the blue regions here turns out to be highly polarized. And that's because, unlike most of the optical light one sees in the Universe which comes from the thermal emission of gas — gases at a typical temperature of 1000 degrees, all that blue light there is synchrotron radiation. There's a huge source (at this point it is unclear what it is) that's generating high energy electrons that spiral in the magnetic field of this nebula and produce lots of synchrotron radiation. So lots of interesting physics to talk about there.

We didn't know for a long time what the source of these high energy electrons was until someone noticed that there were two little stars at the center, and one of those little stars was a little peculiar in that it turned on and off. So Fig. 31 shows two pictures taken 15 ms apart in which you see there's a star and then there isn't. It turns on and off 30 times a second. You might say, "Why didn't anyone notice that?" That will give you the option to talk about the flicker-fusion threshold, how your eye can pick up about 20 or 25 flashes per second until it sees continuous light, which is why you can watch movies that go by at 36 frames per second, and it seems like continuous light. But when you look at this star through a big telescope, and you can see it's a fairly bright star, it just looks like it's shining steadily. Of course, you can use the strobe effect to make your flicker-fusion threshold higher, so you can go to the 200 inch telescope where you can put your fingers like this and you can move them up and down like this and before the men in white coats come and take you away, you can actually see the star turn on and off because you strobe against the frequency of the star which is about 30 Hz.

And if you had looked in x-rays, it would have been obvious what was going on, because that little star, and you don't see any other stars, at least not that bright, is enormously bright, generating huge amounts of x-rays at the center of this nebula, and all of that radiation that you see there in the x-ray part of the spectrum from 0.1 to 10 keV is synchrotron radiation. So that means that you have very high energy particles, the magnetic fields there are only milligauss, and so you can give that as a homework assignment: What is the energy of the electrons you need to get keV x-rays in a few milligauss field?

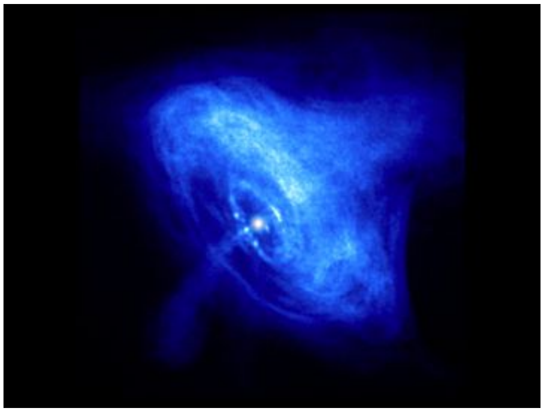


FIGURE 32. X-rays from a neutron star at the center of the remnant.

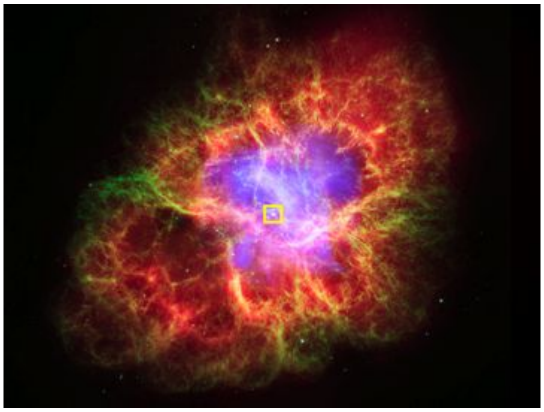


FIGURE 33. Composite of x-ray, optical, and infrared images of the Crab Nebula

And, as Fig. 33 shows, when you superpose the x-ray image on the larger infrared-radio image, the x-ray image is much smaller. Well, why is that? So you can give another homework problem: What is the lifetime of a particle of this energy in a milligauss field? And you find that the lifetime is enough to go a couple of years (it's a couple of light years across) but not enough to go 10 years – this distance – whereas the radio photons

FIGURE 34. Pulsar wind in supernova remnant G292.0+1.8

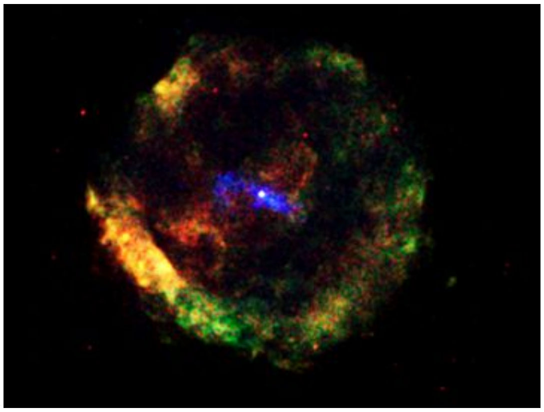


FIGURE 35. Remnant of supernova 386AD

FIGURE 36. Supernova remnant Kes 75 and its pulsar wind

which are coming from much lower energy electrons in much bigger synchrotron loops, of course live for thousands of years, and so you get this slowly expanding radio nebula embedded in the middle of which is an x-ray nebula whose size is limited by the lifetime of the electrons produced by this single neutron star at the center of the nebula.

That neutron star nebula is not always so obvious. Figure 34 is the remnant of a supernova that went off in the Southern Hemisphere in the last thousand years, but since there were no literate peoples in the Southern Hemisphere, we don't have any record of it. And it's really hard to tell that one of those little white things is a neutron star and that slight purple area, which again is the higher energy x-rays, corresponds to the synchrotron nebula in this expanding supernova remnant where here the thermal gas clearly dominates the x-ray emission completely.

The amount of particles (or light) produced by these spinning neutron stars is a strong function of their rotation rate, and the rotation rates range from, in the case of the Crab, 30 ms up to a couple hundred ms. A couple hundred ms is . . . 6 or 7 times slower, and it goes as some power of that – cubed, fourth, I can't remember — but, whatever, you don't always see it. Figure 35 shows the remnant of supernova 386AD where again there's an expanding ring of relatively soft x-rays of all the material thrown out by the star, and in the center a bright little neutron star producing this little blue synchrotron nebula.

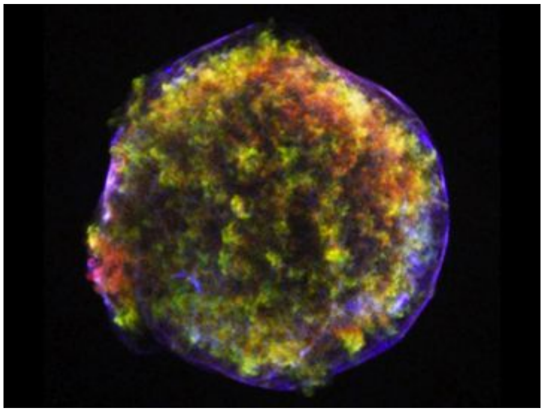


FIGURE 37. Tycho's supernova

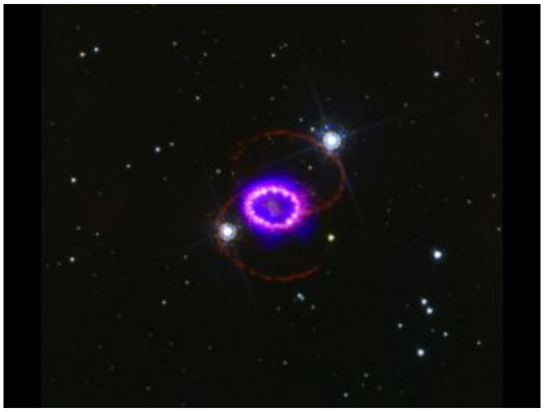


FIGURE 38. SN1987A our nearest supernova

And Fig. 36 shows a remnant that happens to be about 20,000 l.y. from Earth. Never recognized before, never seen today in optical light like the Crab, it turns out to be younger than and more energetic than the Crab Nebula. And, again, you see the expanding shell of synchrotron emission and in the center a neutron star that's got a magnetic field and a spin rate comparable to that of the Crab, and it's producing almost as much energy – completely invisible at visible light. We detected it first as a radio source, pointed the x-ray telescope, and despite the dust and gas along the line of sight, the x-rays can penetrate and we can get a picture.

Some supernovae don't come from the core collapse of massive stars but from the thermonuclear detonation of a white dwarf. And Fig. 37 shows one such supernova. And if the star explodes completely, you don't expect a neutron star left behind. And in the center of Fig. 37 you don't see anything. What you do see is another of one of these rings of blue material around the outside, and that's because while the central stuff is this boiling mess of elements cooked up at temperatures of 5 million degrees, and , therefore, emitting thermal x-rays, this stuff around here is the result of particles accelerated by the shock expanding into the interstellar medium in exactly the same way when you bring your ping-pong paddle and your ping-pong ball as when you bounce your ping-pong ball off the table and then move the paddle down quickly – r. . . . r. . . r.. r. r. R.R, faster and faster. Well, as the shock waves impinge the interstellar medium they're compressing the magnetic field there; particles get caught; they get reflected back and forth; they accelerate faster and faster in a process called first-order Fermi acceleration, and they get up to energies sufficient – even in the weak fields here, which are probably hundreds of microgauss – to radiate synchrotron radiation, and you see that around the outside of the shell right where the shock and its moving particles are being separated. So lots of E&M problems there.

And we are tuned into the star in Fig. 38 because we're only a few months away from the 25th anniversary of the only supernova we've ever seen blow up nearby, and that's SN1987A. It occurred on February 23, 1987, a date I remember because it's my wife's birthday. (Actually, I remember my wife's

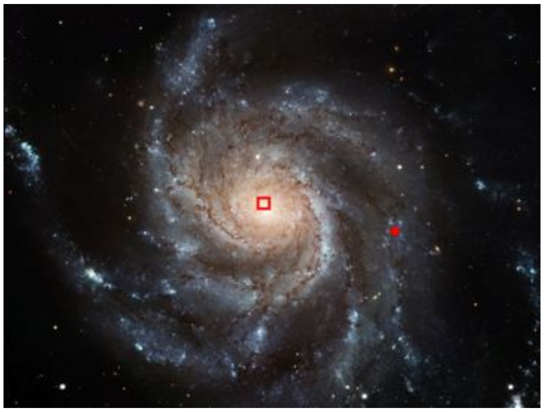


Figure 39. If you consider M101 (the Pinwheel Galaxy) as a proxy for our own, our Sun would be located at the red dot.

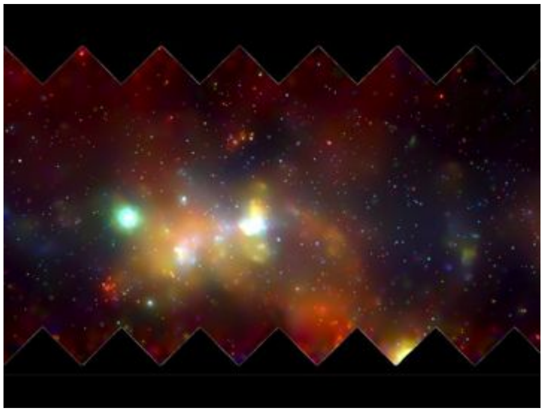


Figure 40. Optical view toward the center of the Milky Way

birthday because it's the day the supernova blew up.) So there was an explosion and the red rings are material blown off like those other stars you saw before, but we have a superposed x-ray picture showing where the innermost ring of that material has now been, just in the last few years, hit by the shock wave expanding at about 10% the speed of light from the supernova, and as the shock plows into this ring of material, it has lit up like a series of pearls on a string there. Quite beautiful. And what we're watching here is the formation of the supernova remnant as it transitions from an explosion which we saw to one of these remnants that are typically a few thousand years old.

In this proxy for our Galaxy (Fig. 39), we exist at the red dot. So we're out far from the center, and if we look in visible light we have a picture of our Galaxy. It looks like we're not outside it. If we look toward the center of our Galaxy, we see dark clouds of gas and dust. They accumulate along the line of sight, and you can't see with visible light because the dust is impenetrable by the optical photons. But as Fig. 40 shows, it's fine with x-rays, and if we point an x-ray telescope at the center of the Galaxy, we see that it's a pretty exciting place – bright lights of New York. Hundreds and hundreds and hundreds of individual sources, some of which are neutron stars and white dwarfs accreting from companion stars.

But big glowing clouds – these big glowing clouds are interesting. If we look there in radio wavelengths, we can see they're big clouds of cold neutral gas, and they're being somehow fluoresced by x-rays. But in the center of our Galaxy there's no bright source of x-rays . . . today. But we know in the center of our Galaxy there's a 3.6 million solar mass black hole, and if that eats a star, it's going to produce a lot of x-rays. And so what is postulated is that, since these clouds are a few thousand light years from the center of the black hole, a few thousand years ago our black hole in our Galaxy was a lot more active, as we see things are in some other galaxies, producing a lot more x-rays.

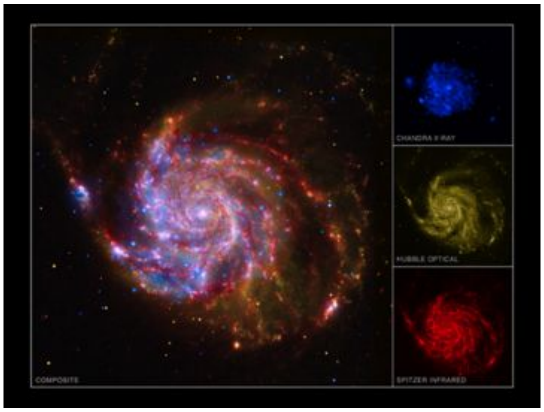


FIGURE 41. M101 viewed as a composite of infrared, optical, and x-ray images

FIGURE 42. Forming stars blow giant bubbles in NGC 604. The picture is an overlay of Chandra x-ray and Hubble optical images.

And what we're seeing is the echo, if you will, as what happened thousands of years ago fluoresces these clouds.

Figure 41 shows how this pan-chromatic or multi-spectral approach gives you an opportunity to talk about putting the symphony back together again by observing the same object in x-rays (blue) and in visible light (yellow) and in the infra-red with a series of satellites, each optimized to one of these octaves of the spectrum. And then putting them together to make a multi-spectral false color image where different wavelengths correspond to different colors.

In Fig. 41 you can see the global structure of this galaxy. You see there are the spiral arms which stand out very brightly in the infra-red where there are big clouds of dust diffused gas, and then you see along these clouds – this arm over at the left is particularly good – there really is a burst of blue where these clouds become dense enough to form one of those big clusters of stars. The stars turn on; their stellar winds go off at about a 1000 km/s; they blow away the gas; they shock the gas to x-ray temperatures; and you end up with bubbles of hot gas along this arm as the star formation starts to take place. So it's a way to visualize what's going on quite dramatically.

And if you zoom in on a region that's part of a local group, you can see huge numbers of stars being formed, big bubbles being blown, and the bubbles are filled with blue which is the x-ray gas (Fig. 42). So the structure of the interstellar medium is such that while most of the mass resides in these dense clouds — with densities from a few 100 to 10 million particles per cm^3 – most of the volume of the gas is in hot diffuse gas at temperatures of a couple of million degrees, therefore forming x-rays, and densities of 10^{-3} particles per cm^3, and the structure of the interstellar medium is revealed in these multi-spectral pictures.

Again, looking at galaxies in different wavelengths shows you different pictures. Figure 43 shows a wonderful galaxy with a visible light picture, and this dark green dust that shows you the plane of the galaxy where

Figure 43. This Hubble optical image shows M104 (the Sombrero Galaxy) which is nearly edge on to Earth.

Figure 44. M104 viewed in the infrared.

Figure 45. M104 in x-rays.

Figure 46. M51 (Whirlpool Galaxy or NGC 5194) is interacting with the smaller NGC 5195 galaxy.

stars are forming. If you look at this (Fig. 44) an octave lower, in the infrared of course, that dust at a few 100 degrees glows, so now it's the brightest thing in the galaxy. And if you look at it in x-rays (Fig. 45), it disappears because it's not hot and it's not dense enough to block the light, and so you see all the bright sources of x-rays all over the galaxy shining through as though that dust weren't there at all. So it dramatically illustrates how looking in different wavelength windows gives you a very different picture of what you see.

Galaxies, of course, sometimes collide with each other (Fig. 46). That can be fairly spectacular as in the instance in Fig. 47; these are visible light photographs. As the velocities of these collisions are 100s of km/s that

FIGURE 47. The Antennae Galaxies are colliding.

FIGURE 48. M82 ejecting material as a result of collision with M81

allows the gas to collide and form new generations of stars which blow out material from the galaxy because of the amount of energy involved. And again, we see that this material leaves the galaxy – the little light material is red. This space between is filled in by the blue light (Fig. 49) because the shock gas even at a few 100 km/s has a temperature of millions of degrees and the gas flows out of the galaxy as a source of x-ray emission.

FIGURE 49. Composite view of M82 viewed in infrared, optical, and x-rays.

Also flowing out of the galaxy can be jets of material as a consequence of some mechanism which Blandford once claimed he understood but I'm not sure anyone really does. When matter falls into a black hole, sometimes it gets ejected as well. So it falls in along the equator, and it is ejected out of the poles and these kinds of jets have actually been seen in the optical but they are really pretty spectacular in some galaxies in the x-ray. In Fig. 50 you see one that's thousands of light years long emerging from the black hole at the center of this galaxy (M87). These jets have been known for a while from radio observations. The picture in Fig. 51 is quite a beautiful example of the global effect of this ejection of material from black holes in nuclei. In blue here you have the x-ray taken right opposite the galaxy, and you see that there's a big cluster of galaxies here.

And when you look, you see a hundred, maybe a thousand, galaxies of stars, each galaxy contains maybe, you know, a hundred billion five hundred billion stars. This is a really impressive number of the mass of the stars, but it turns out most of the mass

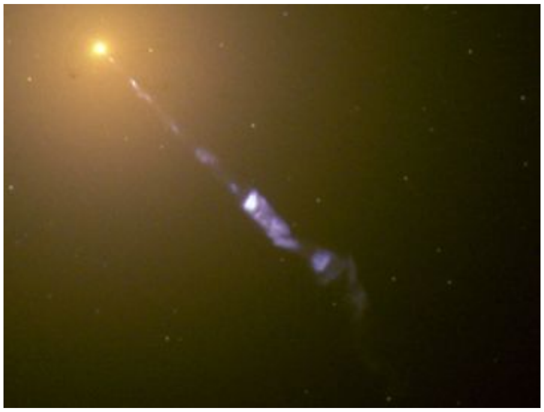


Figure 50. Jet of matter ejected from M87 at nearly the speed of light; the jet is 1.5 kpc long.

Figure 51. X-ray image of jets from supermassive black hole at the center of Centaurus A.

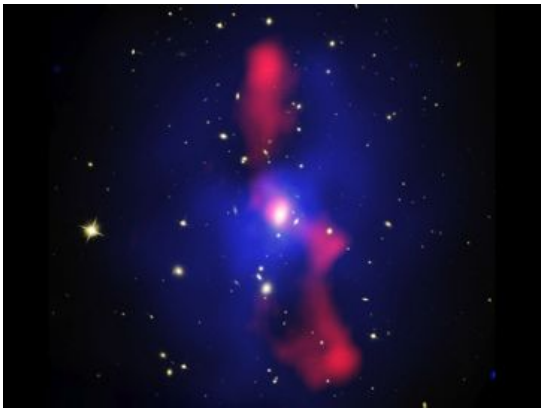


Figure 52. Galaxy cluster MS0735.6+7421, combined optical (yellow), X-ray (blue) and radio (red) image.

Figure 53. Massive cluster of galaxies – Abell 1689.

of normal matter in clusters of galaxies is in the hot – 10 to 30 million degree – gas that suffuses the entire cluster. In Fig. 52 there could be up to 10 times as much mass in this hot gas as there is in the stars in the galaxies themselves. And that is the blue region that you see in Fig. 52. But the galaxy at the center has a very active supermassive black hole, and it's shooting out material, and what you see in red are places where two cavities have been blown in this hot bubble of gas by radio synchrotron photons that have been shot out of this galaxy over the last several million years. They have evacuated parts of this cavity and pushed away the extra gas.

These clusters can be quite spectacular as in the famous Hubble picture shown in

FIGURE 54. Composite optical and x-ray image of Abell 1689

FIGURE 55. Bullet Cluster with two colliding galaxies and a map of their dark matter.

Fig. 53. What we see there is probably a thousand galaxies. Every little yellow blob in there is a galaxy with 50 billions or half a trillion stars. But the interesting thing about this picture is these little arcs. See the blue arcs; there is one around 12 o'clock in Fig. 53? Well, these little blue arcs are a consequence of gravitational lensing of background objects by this huge collection of mass in the foreground. What you're seeing is objects that are several to 10 billion light years away being magnified and distorted by the gravitational lens of this huge amount of material here, again, only a few percent of which is seen in all those stars that your eyes can see. Another factor of 5 or so is in the hot gas which suffuses the whole cluster and appears as the blue glow seen in Fig. 54. And another factor of a few is in the dark matter which makes up the dominant component of mass in the Universe.

Deconvolving the images of those distorted galaxies, we can make a picture of where this dark matter lies. Now the dark matter is something we don't see in any wavelength, but it is there in blue all over the place. And when clusters come together we can get a really dramatic picture of the difference between normal matter and dark matter.

Here's a beautiful example. It's called the Bullet Cluster where we have a big white collection of galaxies over there and a smaller collection of galaxies over there. In Fig. 55 you see two masses of galaxies that have passed through each other some time in the past half billion years or so. Each of those clusters of galaxies has these huge clouds of x-ray gases associated with it. And each of them has their huge amount of weakly interacting dark matter associated with it. Well, weakly interacting dark matter doesn't interact. So when the galaxies go through each other – of course, they never hit; because they're spaced by such big distances – they just pass right through each other. And the dark matter follows them because it doesn't interact. But the gas in these two huge collections of 10^{13} or 10^{14} solar masses of hot gas slammed into each other and as a consequence got left behind. So here the blue is

Figure 56. Hubble Deep Field shows galaxies far back in time.

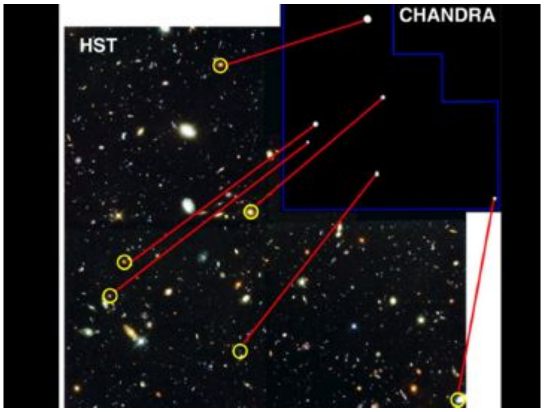


Figure 57. Inset is the Chandra x-ray image of the Hubble Deep Field-North; brightest objects may be accretions onto supermassive black holes.

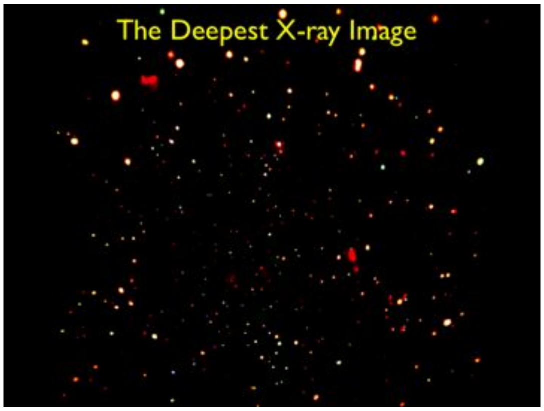


Figure 58. The Chandra Deep Field-North image shows an x-ray view of the region observed in the Hubble Deep Field at optical wavelengths.

the dark matter, and the white is the optical. You see the dark matters follow the optical galaxies as they pass through each other, and yet the x-ray gas has been left in the middle, shocked by the collision of the two clusters of galaxies when they went through. It's quite a dramatic demonstration of the fact that dark matter exists, that it follows the galaxies, and that it doesn't interact.

When we take very deep pictures of the Universes, we see galaxies from local galaxies to red shifts of 6 or 10 to 12 billion years back in time.

When we take the same kind of picture in x-rays, we don't see nearly as many of these objects because we don't see stars that are at temperatures of 5000 degrees; we only see things that are at much higher energies like supermassive black holes. So the Hubble Deep Field (Fig. 57 when it was first observed with Chandra, when it was launched 10 years ago, found a grand total of 1, 2, 3, 4, 5, 6 of the several thousand galaxies here. And notice (Fig. 57) there's very little correlation: I mean these two are pretty bright, but this guy's pretty faint. That one's really bright. It's just what their black hole is doing in the center as to whether we see them or not.

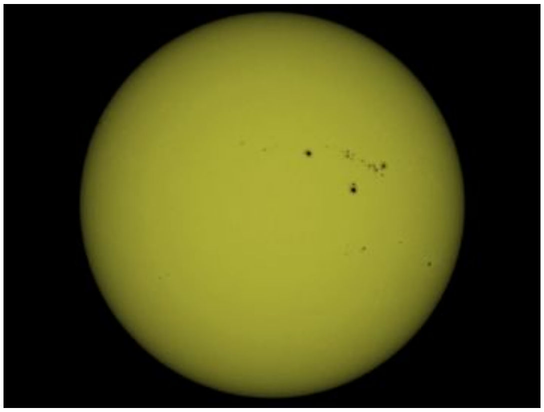


Figure 59. The Sun as seen in optical wavelengths.

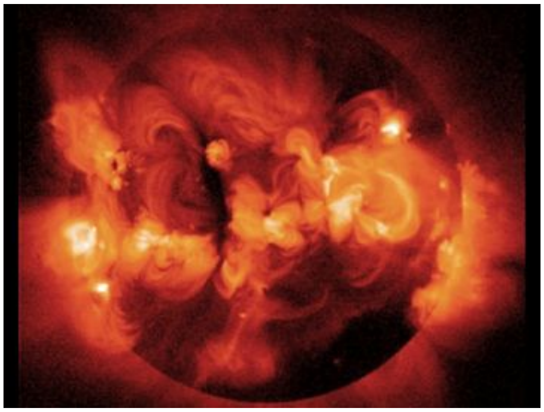


Figure 60. The Sun in x-ray wavelengths.

Subsequent to this we spent a lot more time with Chandra, and Fig. 58 shows the deepest x-ray look at the sky to date. It doesn't look so different from the optical picture although there are many fewer sources per square degree. Okay, colors represent temperature, the energies of the x-rays. And you see there's a very different Universe there that doesn't match at all.

So I guess I would conclude that if you want to excite your physics students by making sure you confine them to seventeenth century physics for the entire first year, or maybe nineteenth century if you get to E&M the first year, if you want to make sure they learn physics just like you did, and, as at Columbia for the 54th year in a row, you use Halliday & Resnick, then you show them a picture of the Sun like Fig. 59, but if you want to get them excited about physics and all the interesting careers that are possible therefrom, then you show them a picture of the Sun that looks like Fig. 60.

Questions

C: Time for some questions. We've had a full course of modern astronomy in a very short time.

Q: Why do Sun spots look dark? If they're hot, wouldn't you expect as a black body it would still be brighter at 5000 K ?

DH: You're seeing different layers, right? And where the Sun spots occur, you've got a disruption of magnetic field from below the surface of the Sun. That lowers the pressure there, so it lowers the amount of emission you're getting. So it's not actually black; it's that relative to the surrounding region you're getting less optical photons because there is less gas there because the magnetic pressure is supporting part of the pressure. And what happens with the magnetic disruption of the surface is that their poles move together and they annihilate, the north and south poles annihilate with each other, releasing huge amounts of energy which heats the gas to high temperatures and it gets thrown up into loops of magnetic field there. And there's a whole complicated thing going on. We really don't understand it all that well. And imaging in the 10 to 80 keV range, which the satellite will do, as you see the little Sun spot go around the edge, it will allow you to do a vertical profile of how the x-rays are being emitted. So for our closest object that's pretty easy to study its photons, there's a lot of mysteries about Sun spots. And, of course, they're important because they dominate space weather. And, as I say, stars are thought to be much more active when they are first formed – there's evidence for that – and that might well have modified the formation of the solar nebula from which the Earth was formed. So there's lots of interest in them.

Q: (Galvez) Usually when we teach astronomy we're thinking of Newton's Laws. But it seems like with this new x-ray view we may have some access to studying electromagnetism using a lot of images and a lot of things.

DH: Electromagnetism here; you've got nuclear physics and nucleosynthesis; you've got atomic physics in the intera well, the absorption of the atmosphere to the interactions of all these particles; lots of fluid dynamics, because all these things are dynamic and shock waves and all this other stuff. So, yeah, I think there's a great richness here. Again, our eyes see one octave. It's not surprising we don't see everything that's going on. These pictures are dramatic because they are dramatic: we're looking into violent, high energy regions of the Universe. And all this other physics comes into play.

Q: (Kevin McLin) Dave, you talked about a course – a reading course – that you teach at Columbia where you probably do some of this with the students. Have you thought about how you would put it into a majors' course? That's why we have this conference here. For the major students . . . it's very inspiring for the introductory students.

DH: Well, you know 99% of our students are not majors, so that's why I focus my time on them, because even getting 1% of those will double the number of majors we have. It's a real positive thing. Yeah, there are a few things that I have done that are relevant to majors courses – not particularly related to x-rays, necessarily. I did once teach a class for graduate students that went through all of the instrumental techniques for focusing, collecting, and detecting and analyzing x-rays. And there's just lots of good physics in that. You could build a whole course around it. The question is: "How do you take little snippets of this – I think this is our goal – and inject them into your Resnick & Halliday course. And that's what we're here to draft.

C: I hope so. I think that it isn't just that we want to take snippets. I just don't think there's another way to do it.

DH: I agree. The innate conservatism of most faculty

C: That, and also to get a handle on it . . . to physicisticize astronomy you have to do something like that.

Q: (Amato) I wanted to ask about something very specific, and that would be gravitational lensing. Can you see a way that could be included in a first year course? Or is just out of reach.

DH: Well, without using tensor equations you can just use the geometry. You just do the geometry. You know: Where do you put the lens? How does it change the lensing? Why does the midpoint between you and the source give you the maximum effect? And then moving the lens around. I mean people have made these wonderful plastic gravitational lenses. Right? And so you can move them around and you can also do it on the computer.

C: I don't know about this.

DH: Yeah, who had one of these? So you can give people a visual impression of what is going on, and then just do the simple plane geometry of how the rays are traced. And that's fine for an introductory course; yeah, I wouldn't do tensor equations.

Q: (Blandford) It's not necessary to do tensor equations. In [Sun Hong] Rhie & [David] Bennett there's a quite simple approach. It's just like doing things in flat space with a refractive index equal to $1 - \frac{2GM}{rc^2}$. So if you just take that as the effective refractive index, it's just like doing matrix optics in flat space. That's a perfectly good approach, and I think it's quite appropriate for a first year course.

C: So this sounds like a good topic to take up in a breakout session.