ASTRONOMY UPDATE 1993

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Abstract: Astronomical research during 1993 is reviewed, beginning with status reports on several groundbased and orbiting telescopes and planetary spacecraft. Solar system topics include Magellan results from Venus and impacts on various surfaces of meteorites, comets, and the solar wind. Stellar topics include new high-precision parallaxes, sites of active star formation, and interactions between stars and the interstellar medium. Other topics include the Hubble constant and interactions between galaxies.

Thank you once again. It is an enormous honor for me to be asked to speak to you so many times. It's always a treat to come in to talk to people deeply interested in astronomy and able to communicate it to the public and without whom there would be no astronomy. Thank you very much.

I had a real treat coming over here. I left Champaign at 5:30 in the morning in complete darkness with Venus in front of me and followed it here. Without it I probably would not have been able to find my way. You get to watch the twilight come up, you get to watch the Sun rise, and it makes you realize why you became an astronomer in the first place.

Telescopes and Spacecraft

We are mourning Pioneer Venus, which died this year. It had a wonderful life. It helped make the first images of Venus's surface and is now gone, replaced by Magellan. We mourn Mars Observer. This is a secret government photograph showing Mars Observer zooming past the planet earlier in the year. We don't know where it is. I suppose it is in orbit but it doesn't matter since we can't communicate with it any longer. We mourn Galileo's antenna. After ten thousand hammerings, it's still stuck. It doesn't work. Nevertheless, the low gain antenna does work and the spacecraft acquired some marvelous images.

Galileo made the second photograph of the Earth and Moon together from space. This is a highly foreshortened view, as we know one is not that close to the other. What's remarkable are the color differences—compare this wonderful blue planet of ours to the dead-looking surface of the Moon; dead-looking until you look at it in false color. The first time I looked at this slide, I said, "Oh my gosh, the false color crazies are at it again. They've done this awful thing to the Moon." Then I read the description, which I should have done in the first place. Then you realize that this really is a composition map of the Moon made by the spacecraft, where the blue areas show regions high in titanium and the lightly colored areas are low-metal regions. It shows you rather nicely that the mare lavas tend to be high in heavy elements, and the highlands tend to be low in heavy elements, which supports the idea that in the early days of the Moon, the heavy stuff sunk from the highlands and resurfaced as the mare lavas.

We also mourn the 26-meter telescope at Hat Creek. We had another one crash down on us. The wind blew it down. There are no plans for putting it back together again, I'm afraid.

We are horrified, not mourning, at space advertising. You remember the folks who tried to fly coffins around the Earth a few years ago? If Uncle Ed died, there was a company in Florida that could put him aboard a bright cylinder launched from Florida. You could then watch Uncle Ed fly over every ninety minutes. In the words of Dave Barry, "I am not making this up." Well, it got shot down, but then there was another company that wanted to float advertising with a mile-wide mylar banner of some sort. That seems to have been shot down too. The perpetrator of this evil deed was actually quite shocked at the reaction. People really didn't like this idea of a Pepsi bottle flying overhead.

We are also probably even more horrified at the possibility that the Russians may fly a giant reflecting mirror to illuminate spots on the ground. This idea has been around for the last twenty years. I think all of us, and many others in our position, must be at the forefront of the fight to do something about it to keep it from happening. It hasn't happened yet and I certainly hope it never will.

So we go from mourning to being horrified, to celebrating. This is a celebration of — this in my home territory — the Hat Creek array of six microwave radio telescopes put together in an interferometer. It's the world's most powerful microwave interferometer. It's run by Berkeley, Illinois, and Maryland, so I'll pump up Illinois at least a little bit. It's doing some remarkable imaging with such high resolution it can zero in on interstellar clouds. And as a result, Lew Snyder of our department recently found, probably with a 90% certainty, interstellar glycene, the first amino acid to be discovered in interstellar space. How complicated does chemistry get out there? Remember that there are amino acids in meteorites. How did they get there? We begin to see the interrelations between interstellar space, interplanetary space, and the planets themselves.

Celebrate also the Very Long Baseline Array, a real radio telescope that stretches from the Virgin Islands to Hawaii. This is a link of it in Arizona. These are all unconnected instruments, and they are linked together by computer and atomic clocks after they have made their observations. All the telescopes make simultaneous observations that are keyed with atomic clocks and then the computer can determine the interference pattern from which the image can be reconstructed with a resolution that approaches a ten thousandth of a second of arc. I started this series of talks to you five years ago at Staerkel Planetarium in Champaign, thanks to Dave Linton. If there has been one constant theme through all the talks it has been the search for resolution. You can't beat resolution. If you get a fuzzy image, you might as well have no image at all. The ability to see into the hearts of quasars, for example, is paramount; without that we know little. This is the first dedicated large interferometer that allows us to do it on a regular basis.

We also celebrate the 100-inch telescope with which Hubble discovered, in a sense, the existence of galaxies. He found that Immanuel Kant was right: that there really are island universes. Those fuzzy blobs out there are real galaxies. The telescope almost died; in fact it was closed down because it's in a terrible location. If you think it's bad here, try looking over the Los Angeles basin. The flux of electromagnetic radiation is also so powerful, because of half a dozen nearby radio transmitters, that they have to put a cage over the electronics. In any case this telescope has now been resuscitated as a high resolution instrument for adaptive optics, and it will probably wind up at the forefront of astronomy within the next few years. Astronomy is one of the few sciences that can use instrumentation a hundred years old. After all, the forty inch Yerkes refractor is still working. How many people are doing front-line research with hundred year old microscopes? Not too many.

We also celebrate the IUE, the International Ultraviolet Explorer, of which the public knows almost nothing because it's a spectrographic instrument. It doesn't make pretty pictures. This remarkable device was set aloft 1978 with the three year lifetime. It's now going into its seventeenth year. Someone decided to put a 50-year supply of hydrazine propellant aboard. It's still working on two gyroscopes; four of them are dead. NASA may close it down in spite of the fact that it is oversubscribed by a factor of two or three. We may be mourning this little fellow next year. It has only a sixteen inch telescope, but it's been a workhorse of astronomy for the last 16 years.

Celebrate also the Compton Gamma Ray Observatory. This is an all-sky gamma ray map showing you the gamma rays coming from the plane of the Milky Way. This telescope has shown us as well that mysterious gamma ray bursts are coming from all over the sky. They are uniformly distributed and no one has any idea of what they are.

The Hubble Space Telescope we will celebrate as well. Everyone thought was a dud when it was launched, but it has produced some remarkable images and some remarkable science. As an example, look at this image of Io. You can see the volcanoes on Io from the Earth.

The Planets

Mostly we celebrate Magellan. I think I have shown this slide every time I've given this talk. It's an artist's conception of Magellan orbiting Venus. There has been something new to say about Venus every year. I just want to show you a couple of the more interesting results that have come from this satellite. Since the data are digital you can look at any point of view. You're looking across the plains of Venus between Beta Regio and Aphrodite Terra, at Sif and Gula Mons off in the distance magnified vertically by a factor of twenty. The whole surface of Venus appears to be covered with volcanic structures of kinds you cannot see on Earth. This is called a corona and it appears to be a volcanic uplift with a center and radial cracks coming out of it. We now believe that most of the topography of Venus is being raised by volcanic plumes and has very little to do with tectonic processes of the sort that we have on Earth. It seems to be a single-plate planet, which is rather remarkable given the fact that it is almost the same size as the Earth and has 80% of Earth's mass. Why aren't they more similar? Venus is a little closer to the Sun, has a higher temperature, and a much denser atmosphere, which raises the temperature of the rocks to something close to the melting point. So the atmosphere has a very powerful effect on the rocks and that may be why Venus's surface is so different from our own. You can look across the plains of Venus and see meteor craters. The meteor craters are well distributed across the whole surface of the planet and they do not seem to be particularly degraded by volcanic action. From the density of the craters (the number of craters per million square kilometers), we can make an estimate of the age of the surface based upon what we know about the age of the Moon and the density of lunar craters, which we have dated absolutely. What we find is that the whole surface of Venus seems to be somewhere around a half a billion years old. The idea is that the whole surface of Venus simply turned itself over half a billion years ago and may do this periodically; it is quite different from the Earth. That is consistent with the fact that Venus has no magnetic field, which suggests that Venus's core is cold and solid. What is happening is that when the surface of the planet turns over volcanically, it lets a lot of heat escape which chilled the core. It is only three tenths of an astronomical unit from us, and look how different it turned out.

Moving from Venus on to the Earth, the giant meteor crater off the Yucatan Peninsula has been dated at about the same time as the KT boundary, the time when the dinosaurs appeared. It gives a little more credence to the idea that the dinosaurs and many other life forms were wiped out by a large meteorite impact. This may in fact be the one. The collisions have become politically popular. When you need money, you come up with something new. The new idea is the Earth is going to get hit, so let's look for all the asteroids that might hit the Earth; then we can soak NASA for ten million or twenty million or a billion dollars, and build lots of telescopes to track them all. Then we shoot one down if it happens to be bearing down on the Earth. That we are likely to get hit is in fact indicated very nicely by this slide. It shows the orbits of Earth-crossing asteroids. It's not too surprising that we get hit once in a while. In fact every year we suffer some kind of a near miss. This is 1993 KA_2, a little asteroid about ten meters or so across that passed about ten Earth diameters away from us. As usual we don't see it coming in. Oh! There's one now going past the Earth. It didn't hit us, but the likelihood of a strike is very strong. If you don't believe that, take a look at this poor young lady examining her car. Over the last three or four hundred years there have been something like sixty hits by meteorites, including three people and four cars. So apparently it is more dangerous to be in a car than standing outdoors. Just be careful of where you park your car. Fortunately, if this does happen to you and you escape intact, the meteorite is worth more than the car. She was able to replace the car with a much nicer one I believe.

Here is Neptune and the Great Dark Spot. What wonderful names. Of course, Saturn has the Great White Spot, which has a stormlike feature that develops when Saturn's northern hemisphere points at the Sun every thirty years or so. Uranus seemed to be the odd person out. Low and behold, with infrared imaging we see that maybe it has one too. So we are challenged. Is this the Great Dim Dusty Spot? the Great Gray Spot? Apparently the infrared imaging looks through the methane haze and, maybe Uranus has a storm system as well.

Uranus has a long and fascinating history. It had been spotted with the naked eye over the years, and was finally nailed down as a planet by William Herschel in 1781, and initially named after King George III. Since the French and others didn't like that much, they finally just settled on continuing mythological names. Then Uranus misbehaved. It was never where it was supposed to be. The astronomers in the nineteenth century (everybody knows this story) then discovered Neptune using the perturbations of Uranus and predicted its position to within a telescope field of view. It was discovered the first night of observation by John Galle in Berlin. The trouble is that Uranus still continued to misbehave. Percival Lowell decided there must be yet another planet out there. Clyde Tombaugh went after it and looked and looked and looked and finally found Pluto. Pluto was such a wimpy little thing that it became pretty obvious that Pluto couldn't possibly have that big an influence on Uranus. So it has been hypothesized over the years that there is still a planet X out here some where. Astronomers at the Naval Observatory even calculated that it was probably in the constellation Serpens. It had to be out of the ecliptic because the indefatigable Tombaugh probably would have found it. IRAS, the infrared satellite, didn't see it either. Now finally they have factored in the proper masses of Jupiter, Saturn, Neptune and so on, and discovered that Uranus behaves after all. Planet X is a vapor; we don't need it any more.

The calculations of planetary positions have reached remarkable precision. This graph simply stuns me every time I see it. This is the result of perturbation of Mars on Pluto in millions of years caused by shifting Mars in the computer. Here's a change in Pluto's location as a result of shifting Mars by, get this, one millimeter. Only that much. You're shifting it that much and that is the effect it has on this planet. Can we calculate planetary positions very far into the future? I don't think so. Certainly not for Pluto. Pluto has a chaotic orbit. It is impossible to predict the position of Pluto more than a few millions of years in advance. That's probably true of all the planets. Fortunately in the case of the Earth, the orbit is chaotic over a period of perhaps a trillion years, which is longer than the lifetime of the Sun, so who cares.

Asteroids and Comets

Now on to asteroids. Here is Gaspra. You remember Gaspra from a couple of years ago. This is another wonderful image taken by the Galileo spacecraft. It imaged another asteroid as well. But what is remarkable about Gaspra is that Galileo discovered a wake in the Sun's magnetic field behind it. Gaspra is a magnetic asteroid, which came as a great surprise. The Moon is relatively dead. Venus is dead magnetically. The Moon exhibits some fossil magnetism, but nobody expected asteroids to be magnetically active or to have any kind of significant magnetic fields. No one knows quite how to interpret it, but one idea is that this is a fossil magnetism that came from an intense solar magnetic field in the early days of the solar system.

We have a serious problem with the Sun. The theoreticians will tell you that the Sun was 30% dimmer when it was born than it is now. Now life appeared on Earth quickly after the Sun and Earth were born. You dim the Sun down by 30% and we're all going to die. The Earth would freeze over. The Earth must have been fairly warm four billion years ago, warmer than we would expect from the theoretical calculations. One idea is that the Sun, having just been born out of the interstellar medium, was spinning very rapidly, generated a very powerful magnetic field, and was very active producing great numbers of solar flares. Here's a wonderful x-ray image made with the Yohkoh Japanese satellite. You can see these arcs and loops in the corona that cross over and collapse and produce solar flares. The Sun is still very active magnetically, but it may have been much more active four billion years ago, enough to have kept the Earth warm. In fact, flash melts have been found in meteorites that again indicate great solar flaring activity four billion years ago, perhaps enough to produce what is now fossil magnetism in asteroids.

These asteroids prove ever more fascinating. Radar telescopes imaged the asteroid Toutatis, and what was thought to be one asteroid turned out to be a double asteroid, two small bodies either in orbit around one another or perhaps even in contact with one another. The art of radar imaging has improved remarkably. I went to an engineering colloquium a few months ago that showed radar images made of the Moon that rival some of the Apollo astronaut photographs. It's gotten that good. The imaging is much better than you can do optically from the surface of the Earth. I've always been intrigued by this shot, which is a double meteorite crater on Earth; then you look up in the sky and you see double asteroids. This is Clearwater Lakes in Canada; perhaps we can see where some of these double features have come from.

Here is Saturn, home to the Great White Spot, I might add. Where do the rings come from? Nobody knows. There are a lot of ideas. They may have been formed with the planet. They may have been a failed satellite that was so close it was never allowed to develop. That's what I learned when I was growing up. Another idea is that it was a comet that came too close to Saturn, got ripped apart and spread itself around the planet. Over the millions of years the pieces ground themselves into a powder. The rocks that make up Saturn's rings are no more than a few centimeters or so across. There are trillions of them. The idea that they originated through a comet that got too close has been supported by Comet Shoemaker-Levy 1993e, which close imaging shows got too close to the planet and broke into the famous string of pearls. There have been up to twenty nuclei seen in this comet. It's due to impact on Jupiter next year with an energy of somewhere around a billion megatons of TNT. Unfortunately it will hit the back side of Jupiter, so we're not going to be able to see the actual impact itself. There have been some plans to fire up Voyagers camera so that they can look at the back side of Jupiter. They won't be able to resolve it, but they might be able to see a brightening when the stuff dumps into the Jovian atmosphere. It's eminently conceivable that on a different orbit, some of this stuff could grind itself down into some kind of a ring. So you begin to see where at least some of these planetary rings may come from.

Another Kuiper belt object, 1993FW, has been found. This isn't the one. This is the $1993QB_1$. But it's not going to look any different from that. It's just a spot on the slide, but now there are two of them out there. We're starting to probe beyond Pluto into the Kuiper belt, the origin of the short period comets, the disk we think was left over after the formation of the Sun. As our instrumentation gets better and better we may find a thousand, a million, who knows, maybe a billion in orbit about the Sun. It's estimated to extend around a few hundred astronomical units away from the Sun. And then we go out even farther, and we see what might be the heliopause, the region where the solar wind smashes into the gas of the interstellar medium and sets up a shock wave. A powerful flare on the Sun propagates a shock through the solar wind, and apparently one struck the heliopause. The radio emission from the impact of the shock wave into the interstellar medium was picked up by the Voyager spacecraft. It is hoped that the Voyagers will cross the heliopause and enter true interstellar space sometime before there plutonium power packs run out somewhere around the year 2020. This is the first indication, however, that the heliopause truly exists, and we might have observations of it here.

Astrometry

Move on, now, into true interstellar space, to the stars. If you ever visit the southern hemisphere, go outside the first chance you get and see the rising of the Southern Cross and Alpha and Beta Centauri. It's a stunning sight. There's Alpha Centauri and there's Beta Centauri over here. Alpha Centauri is the closest star to the Earth, at least that's what you tell your students. You then might say, "Well, not really, the closest star is Proxima Centauri, a companion to Alpha Centauri." It's an 11th magnitude little flare star that appears to have spots. These flare stars erupt once in a while in gigantic chromosphere flare. There's been some variability that has been interpreted as spots rotating in and out of the field of view. Is Proxima Centauri really part of the Alpha Centauri system? I always learned that it was a distant companion to Alpha Centauri. Modern observations suggest that it may be going too fast and may be just passing by Alpha Centauri. Maybe it doesn't belong to it at all. Nobody outside of this room is going to care about that at all. Maybe it's not a triple star, maybe it's a double star. The argument will go back and forth and next year it will probably be something else. You'll hear the same argument raging on about Mizar and Alcor. Are they real companions or are they not? It depends upon which person you ask. Common proper motion binaries are difficult to work with.

The parallax business has reached remarkable proportions. Let me back up on this one again. Go back to the Proxima Centauri, the closest star. The parallax here is a barn door, it's about 76 hundredths of a second of arc, rendering it approximately about 1.30 parsecs away. They mean 1.30 too, not 1.31, it's that good. When I was a student, in fact only up till ten years ago, the general rule was parallaxes are good to 0.01 seconds of arc. Unless you have a parallax of 0.03 seconds of arc, which is only 30 parsecs, a hundred light years, they're no good; you can't rely on them. Parallax observations have undergone an amazing revolution, largely at Allegheny Observatory in Pittsburgh where they've got devices that can get precisions to one thousandth of a second of arc and have recently measured the parallax of Delta Cephei. It's hard to overestimate the importance of this because we are now able to nail down much better the calibration of the period luminosity relationship without which we can't get distances to galaxies. As we work our way farther out in parallaxes we will get better distances to the Virgo Cluster, for example, which becomes powerfully important in terms of the construction of the universe.

Star Formation

Let's go back and look at stars. This picture of the Orion Nebula was taken with the Hubble Space Telescope. In here what we see are disks around stars, little tiny disks that contain somewhere around a few tens of Jupiter masses. We may be looking at disks around nascent stars, stars that have just formed. The Orion Nebula, illuminated by a very hot O star, is actually a blister on the surface of a massive interstellar cloud, a giant molecular cloud, and it's a region of intense star formation. You just see new stars everywhere.

This video is compliments of Space Telescope. The Orion Nebula is not something you see on a two dimensional sky, it has a three dimensional structure to it. The idea here is we're looking at a new star, one that is blowing off a bipolar flow. As the thing collapses, it spins faster into a disk and then the star in the middle develops a powerful wind that blows through the poles and may be collimated magnetically into a very strong bipolar flow that produces such things as Herbig-Haro objects, which I didn't bring pictures of. The disk is the region in which the planets apparently form. Here's the famous bar in the Orion Nebula, and this in the infrared. Look at this stuff coming out of it. One person suggested some of this may be related to a supernova that occurred in the Orion Nebula, but it may just as easily have been produced by something called an FU Orionis star, which is a grand version of a T Tauri star. These things brighten by several magnitudes and apparently produce powerful bipolar flows, perhaps enough to produce these features, these shock waves within the gas of the Orion Nebula.

The point is we are again seeing active star formation, something that twenty years ago we could not do. We had no clue as to what caused stars. We now see star formation every place we look. You look in dark dust clouds and you see new stars. This is maybe a degree or so across, and none of these stars are visible with an optical telescope. All you would see is a blank area of sky and a thick dust cloud. You look at them in the infrared with the new infrared imagers, which were nonexistent ten years ago, and you can take pictures of stars that you cannot see with the eye through the telescope under any circumstances at all. There are twenty, thirty magnitudes of extinction. So we're beginning to see the individual clusters within the dark clouds before the clusters emerge from the clouds and perhaps even break up.

The circumstellar disks are real. This is the disk around Beta Pictoris. This discovery was made several years ago, but people continue to study it, and they continue to find analogies with our solar system. The disk consists of silicon dust a couple of microns across. They have been able to look right into it and it extends to within 40 or so astronomical units of the star and does not seems to be cleared out. That is, we do not see a region that has been blown clear by planets, yet I think to almost a person, everybody thinks, "Oh, there's got to be planets in there somewhere." Every calculation made of a dust disk around a star shows the development of planets. They seem to be everywhere, except we haven't found any yet.

The disks seem to be everywhere. This is Fomalhaut. When you go out in October or November and look to the south, you see this lonely first magnitude star going across the southern sky, the fish's mouth. In the infrared we see a disk very similar to the one around Beta Pictoris, except positioned so its axis is perpendicular to the line of sight, and you can see the whole thing.

Even normal stars have given us something of a surprise. The Pleiades is enmeshed in a reflection nebula. I used to teach that it is just the left over debris of the formation of the Pleiades. But then you start to wonder how that can be because the cluster is still several million years old. The stuff should have dissipated. A recent photograph actually shows the Pleiades plowing through with it leaving a wake behind it. The stuff around the Pleiades is just an interstellar cloud that happened to be there. The Pleiades hit it and lit it up and it will eventually be out the other side.

Stellar Mass Loss and the Interstellar Medium

The feedback by stars to the interstellar medium gains in importance. I've got three slides that epitomize it. This is a famous object known as the Egg Nebula. Modern imaging has shown a molecular hydrogen disk in here. You can see structure within these flows that are coming out in the center. What you see is that the star is producing puffs of very dusty material. It's throwing itself away. There is probably an advanced giant star in there. It's throwing its outer shell back into the interstellar medium and ejecting dust. These objects seem to be the birthplaces of interstellar dust. The dust becomes modified in the cold of interstellar space where it gets covered with ices and picks up metal atoms, depleting interstellar space of metals. Then of course stars are born out of dusty interstellar gas. They are then surrounded by a dusty disk that produces the planets. So you can trace back the origins of the planets to the dust that had been produced by advanced giant stars, completing a full cycle of stellar evolution.

Mass loss produces some weird effects. Look at this double ring. This is what happens when you have a binary star involved with a giant, in which orbital characteristics produce some of these oddest mass loss characteristics. These objects are linked to the planetary nebulae. A planetary nebula may be the ejecta of one star, but may also be involved in binaries.

The records keep going up. My research business has been planetary nebulae for thirty years and I got involved in a sub-sub specialty by looking at large ones. The largest one I knew of, when I did my last work in this subject, was about a parsec or so across. Such planetaries can span the distance between the Sun and Alpha Centauri. The objects begin overlapping nearby stars. The record is now a remarkable five parsecs across. Here's a planetary nebula, surrounding what is now a white dwarf in here. This distance is almost fifteen light years. You can put several neighboring stars within the span of the planetary, showing that the gas is again dissipating in interstellar space, providing raw material out of which new generations of stars will eventually be born.

Here is Messier 15, a wonderful compact globular in Pegasus. I was out the other night roaming around with binoculars and picked it up with little difficulty from a modestly lighted back yard. It's one of the few globular clusters that appears to be what we call "relaxed". That is, the heavy stuff has fallen to the center and it probably is undergoing no more dynamical evolution. It's quite compact in the middle. One of the prime tasks of the Hubble Space Telescope was to look at the core of this thing. With a groundbased picture, you can't resolve the center of globular cluster. The Hubble got right into the middle and found truckloads of hot blue stars that should not exist. Globular clusters are very old. There shouldn't be any blue stars. We think these are the naked cores of evolved stars. We are not seeing normal evolution; but the density of stars is a million times greater than it is around the Earth. If you lived in M15, you could go outside and have your sky illuminated by thousands of first magnitude stars. The stars are so close together in the core of M15 that tidal forces simply strip the envelopes of advanced giants; you're looking at what used to be the old nuclear burning cores. Such evolution is very different from that in our own part of the galaxy.

Hubble triumphs again with the nova remnant from Nova Cygni 1992. This is the smallest nova remnant ever observed. Nova Cygni 1992 was interesting because it is very rich in neon. It was thought to be a rare case of an exploding white dwarf with a neon-magnesium core. It's not the whole white dwarf that exploded. Novae are produced by double stars in which a main sequence star is tidally distorted and disrupted and throws mass onto a white dwarf. The mass is compressed and then the star's surface erupts via the carbon cycle in a giant thermonuclear explosion. The core of the star really doesn't know what's going on. The surface gets ejected into space and produces this shell, which we will see expand for the next couple of centuries or so. Most white dwarfs have carbon-oxygen cores, and that is the end of stellar evolution. The main sequence hydrogen burns to helium and then when it becomes a giant star the helium burns carbon, but the star can't get hot enough inside to fuse the carbon into more advanced stages like it would in a supergiant, so there it stops. But there seems to be a gray area between most white dwarfs and the stars that produce supernovae in which the core can actually burn to neon and magnesium. And this has been thought to be one of those rare cases; except maybe not. The argument goes back and forth. This is the sort of thing that you don't like to talk to the public about because it makes us look like uncertain boobs. But in fact that's the fun of astronomy. We know this is a magnesium core nova, and then next year we know it's not. Then next year, maybe it is. We fight until finally, after a couple of years, we come to some kind of a convergence. Nevertheless, it's a fascinating object that is very rich in neon and we really don't know why.

Look at the dust in this picture. This is a mosaic made from the Palomar Sky Survey showing the constellation Cygnus. There's the North America Nebula up here. Deneb is right here. Here is the Pelican Nebula. There's the Gamma Cyg complex over here, filled with bright clouds. There's the Cygnus Loop down here. All of this black stuff is interstellar dust, which wasn't even recognized until the 1930's. And then we realized we have an awful problem in getting the distances of stars because we have to take this stuff into account. The dust, of course, is mixed with gas; only 1% of the mass of the interstellar material is in the form of dust. We don't know how complex the interstellar gas gets. Remember the recent discovery of glycene in interstellar space. But the molecules could be so complex that they could begin to behave like small dust grains. Then of course the dust grains interact with the gas, one of the things that builds more complex chemistry in interstellar space. We have just found in the last year or so probable spectral lines of interstellar diamond dust, which just stuns me. You know what it takes to make a diamond? These are not one karat rocks floating around in space, but microgram diamonds, terribly tiny. But it still takes pressure to produce one. You don't just get the diamond from nothing. And yet what do we find when we grind up a meteorite? This is a little vial filled with one trillion diamonds taken from a meteorite. Apparently the same diamonds that are produced by some process in interstellar space find their way into the planetary system. The planets are made out of the dust from interstellar space. The same diamond dust we see out there is the stuff we pick up out of the asteroids and meteorites, yet another link that connects us with our origins in interstellar space.

Where does the diamond dust get produced? It must be produced in shock waves of some sort. Carbon is in interstellar space minding its own business, and then all of a sudden a powerful shock wave passes by, disrupts the molecular structure, and turns some of it into diamonds. The shock waves come from winds from objects such as Eta Carinae, the famous star in the southern hemisphere that at the time of the Civil War shone at first magnitude. In fact it rivaled Sirius and Canopus, so it must have been quite a sight from the southern hemisphere. There is a star of a hundred solar masses in the middle. We know about three or four of these in any given large spiral galaxy. Or perhaps the shocks are produced by supernovae. Here is M8l, everybody's classic two-arm spiral. Right here is supernova 1993J. These things are incredible. At the time of the collapse of the core of a supernova, it radiates a power, including the neutrinos, equivalent to all the visible stars in the universe! The star itself can for a period of time optically rival its entire host galaxy. These things are going to produce very powerful shocks in the interstellar medium. Here's the Cygnus Loop close up. You are looking at powerful shock waves. These are apparently the shock waves that produce the interstellar diamonds.

Pulsars and Black Holes

The by-product of a supernova explosion can be a neutron star, or a pulsar. This thing here, one of the more mysterious objects in the sky, was called Geminga, the Gemini Gamma Ray source, because it was visible in the gamma ray region. It was seen in the constellation Gemini, but nobody knew what it was. It was very mysterious until it was finally picked up optically, and we now believe it to be a neutron star. It must the closest one. It's only a couple hundred parsecs away, and what we're seeing here is its proper motion. It's so close, we're seeing it move across the sky. It may be the remnant of the star that produced what is called the local superbubble. We're actually inside the bubble of a shock wave at a temperature close to a million degrees Kelvin. This may be the remnant of the star that did it, a supernova that popped off not too terribly far away from us. It's total speculation, but nonetheless interesting.

Here is another pulsar inside the so-called Guitar Nebula in Cepheus . Its wake caused by a pulsar that is moving through space at a thousand kilometers per second. Maybe the motion is caused by a collapse that occurs off center, or maybe it is a binary companion that helps give it a kick, but some of these pulsars are moving at amazing speeds for reasons that are still very poorly understood.

This is a picture of a black hole (black screen). Over the last year there have been three interesting candidates, including this one in Monoceros that seems to have a mass of ten to twenty solar masses. You recognize it because it's bright in the X-ray; it has a companion that feeds mass into the black hole, which lights it up. You can't see the black hole itself, but from the radial velocity variations in the companion you can get some estimate to the mass of the so-called black hole, and if it's more than the neutron star limit of three or so solar masses, what else can you conclude but that you have a black hole? So the number of candidates continues to grow.

This is a nondescript globular cluster called Terzan 5. The bright images you see in the center of it are all pulsars. It's estimated that there may be one hundred pulsars within this one crumby little globular cluster, which attests to the vigor of star formation in the early days of the Galaxy.

Move on a little bit farther out into space. This is the center of Galaxy. The center of the galaxy, Sagittarius A, is so bright it was seen (in the radio) in the 1950s. It's the center of the coordinate system of the Galaxy. It can't be seen in the optical because of a thousand magnitudes of dust extinction. It has been imaged in the infrared and we think we can just barely pick the thing out. People have been looking for this for years.

Here is M31 with M32 and NGC205. The nucleus of M31 is as mysterious as our own. The Hubble Space Telescope imaged it. We think it's probably a smallish black hole like our own. But we find but a double nucleus. Maybe it's just a dust lane in a big nucleus, or a double black hole; we don't really know.

Dynamics of Galaxies

These images appeared in both *Astronomy* and *Sky and Telescope* over the last couple of months. There's a suggestion that Maffei 1, which is a massive galaxy but hidden in the Milky Way, and IC 342 were once binary galaxies in the Local Group. They got too close to the Andromeda galaxy, M31. The Andromeda galaxy then kicked them out of the Local Group. The companions fell into the Andromeda galaxy, and we can speculate—may be the source of double nucleus. Some of the debris was also thrown over to the Milky Way.

These speculations show you the possible interactions among galaxies. Galaxies are big compared to the distances between them. The likelihood of a collision is high. Maybe many of these small galaxies in the Local Group, like the Magellanic Clouds, are simply the debris of various collisions. Collisions have a powerful effect upon galaxies. This is tidal streaming resulting from what was apparently was a collision between two galaxies. And then the Hubble Space Telescope imaged a galaxy whose center is rotating in the opposite direction from the outer parts. The phenomenon seems to be the result of a collision between two galaxies.

Here two spirals collide and merge to form an elliptical. I believe I showed this video once before, but it is worth seeing again. It shows a computer simulation (from the Astrophysical Journal*)* of the collision of two spiral galaxies. Now watch. Doesn't it look like the slide? Then they fall into a heap in the middle and you get an elliptical galaxy out of two spirals. We think that that's where many of the ellipticals have come from.

We're looking here into the hearts of the galaxies. This is a ground-based image showing what appears to be a massive black hole of maybe a billion solar masses in NGC4261, with jets streaming out of it and maybe the black hole itself in the middle. This is one of the first indications that these black holes in the centers of galaxies may exist and the first observation of what might be the accretion disk.

This video was produced by Space Telescope; what a nifty view of the core of NGC4261 in the Virgo cluster. This is the ground-based view from Cal Tech. You can see the jets pouring out. These are the jets that you see from active galaxies. They can shoot millions of light years away from the core of the galaxy in a perfectly straight line. Now we zero in on the middle in this Space Telescope view. The galaxy is literally eating stars in its dense core, the black hole itself.

The Hubble looked into the great distance. The wonderful thing about sciences is its natural time machine. If you look to great distances, it takes light time to get to you, that you see things as they used to be, not as they are now, but as they used to be, perhaps billions of years ago. At great distances you see an over-abundance of spiral galaxies. There's too many of them compared to what you have locally, which supports the idea that spirals eventually collide in clusters of galaxies and merge into ellipticals. This is an X-ray view of the Coma cluster, which appears disrupted. The Coma cluster may have been put together from a collision of several smaller clusters. The X-rays are coming from gas that is trapped around the galaxy. Here is the X-ray emission surrounding the NGC2300 group, more evidence yet for dark matter. The galaxy is not massive enough to have trapped all of this gas. Unless there were an enormous amount of dark matter in here, maybe fifty times more mass than you can see visibly, all of this gas should have escaped. No matter where we look, with only with a couple of exceptions, we see this dark matter. The galaxies are literally the tips of the iceberg; they are just the visible part of what is in the universe.

Here is a remarkable gravitational lens. These are two gravitational images of one galaxy. There's a cluster of galaxies in between. The lensed galaxy is very far away, maybe three or four times farther than the cluster. These are individual members of the cluster. From the separation of the images you can estimate the amount of mass that has to be in the cluster. The amount of the mass in the cluster is again about fifty times greater than you can see visibly. What is also remarkable is that the mass has to be highly concentrated to the cluster center. To be so concentrated, it has to be in the form of what is called baryonic matter, protons and neutrons, ordinary matter, not in the form of exotic matter like weakly interacting massive particles and all the stuff that people hypothesize but have not yet observed in the laboratory. So, we're stuck again with the idea what is the dark matter. Some observations suggest that there's ten times as much non-baryonic matter, mass not in the form of protons and neutrons, as baryonic. Other observations suggest that no, it's all baryonic. We don't know. Then, when we think there is dark matter everywhere, we look at such objects as Messier 105 in Leo and there isn't any. I think it's the first galaxy that has a normal rotation curve, and we don't know why. Why do some galaxies have dark matter and others not? There are still some astronomers around who don't believe in dark matter at all, that something else is causing the observed effects. The subject is obviously open to considerable debate.

Cosmology

No talk like this would be complete without showing the most distant something or other. This is the most distant galaxy yet observed. It sort of falls into the who-cares category. But its redshift is 3.8, placing it several billion light years away from the Earth. We don't know how far because we don't know what space curvature to give to the universe. So the distance is almost meaningless, yet it has the highest redshift of any normal galaxy. The quasars, however, go beyond 4.

Remember COBE? It observed the cosmic background radiation. Last year we looked at it the ripples within it. The ripples seem to represent the initial formation stages of galaxies or rather clusters of galaxies. You are now looking back to a redshift of 1,000 and to a time in the age of the universe of approximately 100,000 years. We cannot look earlier than that because the universe becomes opaque. The cosmic background radiation is the radiation that escaped when electrons and protons recombined in the early days of the universe. The ripples seem to be real. They have now been imaged from the Earth, from a balloon.

The Hubble constant issue rages on. If it didn't and we'd nailed it down, I'd probably have given this talk in reverse because it would have been so shocking. Allan Sandage still claims it's 50 km/sec/Mpc. The standard number now is around 80 plus or minus 5 or so kilometers per second per megaparsec. But Sandage and collaborators found a distant Cepheid in a galaxy that had a supernova in it. They used it to calibrate the supernova's luminosity. From supernovae you can get the Hubble constant, and he again found 50. As an exercise, Edward Harrison, at the University of Massachusetts, tried to construct the most bizarre model of the universe he could, consistent with the observations. He came up with one that had a Hubble constant of 10. He did it by assuming enormous mass that distorts our local view of the Hubble constant. We cannot actually find the true Hubble constant until we can work our way out to at least a billion light years from the Earth. The problem is local motions; there's so much mass that the local motions are fouling up our measurement of the Hubble constant. An astronomer tried to get a sense of the local motion by looking at the surrounding few hundred galaxies. We find that the cosmic background dipole radiation looks a little bit warmer in one direction than it does in the other. That's the result of a Doppler shift. It says that we are moving at 620 kilometers per second toward Centaurus. But the rest frame of twenty clusters shows that we are moving at right angles to that, or 500 or 600 kilometers per second toward Lepus, meaning that the whole set of galaxies must be moving at 850 kilometers per second toward Virgo. Everybody have that? That might be what's fouling up our measure of the Hubble constant. We don't know, but it's an interesting thought.

It is certainly something to think about when the Sun goes down and the stars come out, and you see this wonderful sky, with all kinds of stars, which just gives joy to us all. Thank you.