1990 ASTRONOMY UPDATE

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Abstract: A wide-ranging review of astronomical research in the past year, including solar system, stellar, and galactic astronomy and cosmology. Emphasis is placed on results from high-resolution Space Telescope images. Topics include the solar neutrino problem, the many forms of stellar mass loss, the filamentary structure of the universe, and many more.

Thank you so much for having me back. This is a real treat. Last year I was prohibited from talking about the most famous event of the entire year, the Neptune flyby. I get to talk about that this year; unfortunately it is already old news. This year, however, there were no prohibitions. I get to talk about everything, including not only some of the great things that have happened during the year, but some of the great disasters that have happened during the year. When the bad stuff starts, then they let you do anything you want.

Of course the major event of the year is what Dave Barry called the "Hubble Space Paperweight." As he said, "It would have been cheaper to put an Earth-based telescope on top of an 87 mile-high pile of $5 bills." This is the launch of the Hubble Space Telescope, certainly the most spectacular part of the operation at this point. They did get it into a high orbit 300 miles or so up because they had a little bit of trouble with the solar cycle, which was raising the atmosphere so high that atmospheric drag could have brought it back down, which may not have been such a bad thing. They could have then had it fixed on the ground. Part of the problem, of course, was NASA's enormous, enormous hype. It almost got to be embarrassing because this was considered to be the most important event since, get this, Galileo invented the telescope. Perhaps a bit overdone. Of course when you produce hype like that, if you make any mistakes, you are going to fall. The press will be all over you, which of course they were.

Here is the artist's conception of the Space Telescope going around the Earth, and of course, as you would see in orbit, the Trifid Nebula to the upper left glowing brilliantly for you. This is done by the Star Trek people. The thing is actually a technological marvel. It really is. All kidding aside, folks, as they say on TV, you're going to see some interesting things as we proceed through this talk. The telescope works by bouncing the signal off a geosynchronous satellite and then down to earth. There are several earth receiving stations. It's a difficult telescope to operate because being in near earth orbit, the earth occults anything that you are going to view every forty or so minutes. You don't have a very long dwell time on any object, so it's a relatively inefficient instrument to start with. On the other hand, it's the only way you can make it serviceable, so it's distinctly a trade-off.

The mirror is the most perfect mirror ever made; there's no question about that. That's reality. I think the analogy that's generally used is that if the mirror were as large as the Atlantic Ocean, the ripples would be a few millimeters high. The only trouble was that perfection was achieved with the wrong curve. We have been absolutely savaged in the press. I went on television once and commented that I was going to put a bag over my head and call myself the Unknown Astronomer. The political jibes simply went on and on and on and on and on. The problem happened during the grinding at, never forget this name folks, Perkin-Elmer. If Perkin-Elmer ever opens a lens shop in your shopping center, well....

The problem was with the testing. The mirror has a lot of spherical aberration, and they claimed they couldn't test it. You should test the two mirrors together, and that would have been very expensive. It's very difficult to test two astronomical mirrors in tandem. However, the error on the main mirror was so large that an amateur telescope maker could probably have found it for two bucks in his basement, barring transportation costs. The difficulty was with something they call a null lens, which was the tester used to determine the curve on the mirror, and basically they were looking for the grain on the barn door when the barn door wasn't there. They didn't notice that they apparently misplaced the positions of the testing lenses.

Nevertheless, there have been some excellent images returned; that's a surprise. Now the press is not picking that up at all. They're doing very little with it after their initial savaging of the whole project.

This is an example of the kind of resolution you get. Typical resolution on earth is about 1 second of arc in a good site. That's fairly standard, say at Cerro Tololo or even Kitt Peak. This is what the Space Telescope is achieving over there on the right. You can see that the separation, the resolution, is approaching a couple of tenths of a second of arc. It's really quite good. That's come as something of a surprise. What it was supposed to do was to pack something like 80% of the light into a tenth of a second of arc bundle. It's packing only 20%. It's very inefficient. They can get the resolution. They really can, except that they've got to expose 4 to 5 times longer to get it. And that of course is where it really hurts, because a lot of people's programs are just being thrown out the window because there is just not enough time on an already relatively inefficient instrument.

As we proceed you will see some remarkable images that have been taken by the Space Telescope. I've got a deck here of about a dozen or more slides that have recently come down the pipe from the instrument. To my knowledge they have not hit the press, or if they have the press hasn't been putting them out. In fact, the ST Institute was supposed to have a press conference last Thursday. I was supposed to get the slides right after that. They weren't ready for the press conference. So they had a press conference with no slides. So as far as I know you may be the first people to see some of these that I have today. I think you will enjoy them. We'll just spread them out during the talk. The situation is not all black, in spite of the difficult time the press has given us. It's bad but it's not black.

We can get it fixed. I don't know if you get that, he's putting glasses up there (on the slide). It's kind of hard to see, but effectively, that what we're going to do. We're going to fly another shuttle in about two years. This was planned anyway. Because of the Challenger disaster, the instruments that are there are already well below state-of-the-art. They're relatively primitive CCDs, Charged Coupled Devices. We really need to have them replaced anyway. So once you replace it, all you have to do is to put a correcting lens into it, and the thing is going to work perfectly. It's just going to take two or three years to get the lens designed, and of course to get on a shuttle flight, which is not a terribly simple thing to do these days.

However, we're starting to achieve the same kind of thing from the ground, at least in terms of resolution. We're not observing ultraviolet, unfortunately, but we are able to achieve good resolution. This is an example of the best resolution from ground-based telescopes ever achieved. It's from the European Southern Observatory. On the left is a standard ground-based picture with about a second of arc seeing disc. Over in the right, they are using instrumentation to improve the seeing. That is, they use interactive optics, a mirror system in which you monitor the twinkling of a star and feed the signal back to a rubber mirror, which deforms to flatten out the wave front that's coming in. You can see that the resolution over there is about 0.2 second of arc, only half as poor, rather the Hubble is only twice as good as that. Given the kinds of things that are coming on line over the next few years, I expect sub-tenth of a second of arc imaging to be done, say, within a decade or so, rendering Hubble obsolete at least in the optical part of the spectrum. Actually we'll get better from the ground. However that's a decade off.

In ground-based astronomy, things have been relatively quiet. Instrumentation is still going up. This is the Keck Telescope still under construction, the 10-meter out in Hawaii. The ground squirrel problem has been settled for Mt. Graham's 8-meter, some of the largest instrumentation being built. You may recall that Mt. Graham in Arizona is about nine to ten thousand feet high. It's one of the best infrared sites in the world, but the environmental activists have been trying to keep astronomers off because of the red squirrel, which are in limited supply. But they have something like a couple of thousand square miles breeding area; the telescope is taking up about a few acres or something like that. Nevertheless, there have been death threats against Arizona astronomers for it. The environmentalists actually cut Kitt Peak's power. This is beginning to sound like South America. They blew up the power to Kitt Peak last year. Kitt Peak didn't know it because they went immediately onto emergency power and several Indian villages went out. So they didn't make a whole lot of friends.

This is the last photograph ever made by the 200-inch. No more photographs are being allowed with this telescope. That tells you something about technology. Photographic plates have photon efficiencies of something like 1%, but the charged couple devices run around 90%, so it's a terrible waste of telescope time to take photographs with that instrument or any instrument for that matter unless you need a wide angle telescope or a wide angle field of view. So you might look at a historical artifact here, the last photo ever for the 200-inch. They're not allowed anymore.

ROSAT was launched recently. That's the Roentgen Satellite, the x-ray satellite that is going to revolutionize high-energy astronomy. Here is a photograph of the moon at x-ray wavelengths. Look at the detail. It's a test photograph. This is just x-ray scintillation from the ground produced by solar radiation. But you can get a good idea from the pixel size just what kind of resolution they are going to get. It's going to produce some marvelous stuff over the next few years. Here's an image of HZ43, one of the hottest white dwarfs known that does not have a planetary nebulae around it. The temperature is approaching 100,000° or so.

COBE, the cosmic background explorer, was launched sometime ago. Its results were returned to the ground last January. It produced some superb results. The idea was to look for the 3 degree background radiation from the Big Bang, which this thing has done. It just is absolutely clearing out anything anybody can do from the ground. Another thing that it did was to image the Galaxy. Here is just an image of the Galaxy made in the various infrared wavelengths that COBE observed; it's probably the best "external" picture of the galaxy. Of course we're off to one side so you can still get the impression that this Galaxy looks like NGC4565, the famous edge-on that you always show as examples of what disk galaxies look like.

The sun has made news. We've just launched a satellite to explore the polar regions. We're in the solar equatorial plane. The plane of the ecliptic is very close to the equator of the sun, which is no big surprise, which means you can't see the poles. They are terribly foreshortened. There is some evidence that much of the solar cycle actually starts up near the poles. So to understand the sun, we've got to have a good look at what the polar regions are like. To get there it's sort of like what we have to do in Champaign to fly to Los Angeles on U.S. Air: you go to Dayton first, and then you fly back in the other direction. Here you go to Jupiter first and then you go to the sun. It's the only way you can launch a package out of the plane of the solar system without the use of several stacked Saturn-5s. You have to use Jupiter's gravitational field both to give it an acceleration and to change the direction. It will go under the southern hemisphere of the Sun and then keep orbiting the sun so we can take a look at the polar regions. It's expected to revolutionize our ideas on how the sun works, which is, let's face it, a very very important thing for us to know.

The solar cycle seems to be winding down. We actually seem to have peaked out last year. The thing is getting a little bit quieter. We had a student observing session on the sun last year where I just simply couldn't believe the number of spicules, flares, and prominences. If you have an instrument to watch the sun, it has just been wonderful. This has been one of the best cycles we have ever had. But it's probably on it's way out. In another five years, you're going to take someone up to your telescope to look at some sunspots and you will tell them, "Well, they used to be there, but gee, we're at a minimum, and aren't you lucky, you can see the sun without any spots on it at all."

The solar neutrino problem is heating up, as they say. It's been a serious problem. This is a picture of the Homestead Mine Neutrino Observatory in Lead, South Dakota where they use a vat of cleaning fluid a few thousand feet below the surface of the Earth to keep cosmic rays out. When neutrinos from the core of the sun, the massless particles that are produced in nuclear reactions, hit the chlorine atoms, they are converted into radioactive atoms that can be detected. You can then count the number of neutrinos coming out of the sun. Over the many years of this experiment, we have found only one-third of the number of expected neutrinos. We thought we knew what was going on in the core. We thought we knew what the nuclear reactions actually were. It's been very disconcerting. Well, maybe there's something wrong with the experiment, but the Komiokande experiment in Japan, the one that detected the neutrinos from Supernova 1987a, also has detected neutrinos at one-third the expected rate. Not only that, it's a directional instrument and it is detecting them coming from the sun. There's no questions about that at all. It's not a background problem. It uses very different technologies. These neutrinos are not coming from the direct proton-proton cycle. They are coming from a side cycle, a fairly rare cycle that is linked to the main cycle. There is an experiment in the Caucasus mountains operated jointly by the U.S. and Soviet Union called SAGE that detects main cycle neutrinos. The number of neutrinos coming out of that is zero. Nobody knows what's going on at all. The more we look at the sun, the less we understand. So you will go to an Astronomy 100 class, or whatever, and they'll tell you that we know what's going on, and you give them the solar cycle and the proton-proton reaction. Oh yeah, we've got this all figured out, just trust us astronomers. We haven't the vaguest idea of what's happening with the neutrinos. It's gotten to be such a long-standing problem that theoreticians have essentially sort of ignored it because they're embarrassed about it. They don't know what to do.

Galileo is on its way to Jupiter. To send a package to the Sun, you've got to send it to Jupiter. To send a package to Jupiter, you've got to send it to Venus. So, it passed by Venus because it was designed for the Shuttle and the Shuttle is not powerful enough to launch it directly to Jupiter, so you've got to use gravitational kicks from both Venus and the Earth. It was launched last year, but it did take a picture of Venus as it shot by, showing us that it still looks the same.

Radar imaging of Venus from Arecibo shows some volcanic flows. This is some of the most detailed radar imaging ever made from the ground. Magellan is one of NASA's real successes; at least after its initial problem with its radio linkage, it is now producing some wonderful results.

Something that I think is important for you to realize, and I didn't really realize it until I started talking to some people who were involved with the Voyager probes, and I think it's something that's important to get across to the public, is that space probes and satellites rarely work when you get them into orbit. At least they rarely work well; they can't. You can't test them on the ground. Not really. How are you going to test it? You can't hang it up in a shop some place under realistic conditions. And NASA's brilliance— the engineering brilliance, not the public relations brilliance— is such that these instruments are designed to be repairable once they are in space. You make them with enough redundancy, then you try to think of all the possible things that can go wrong and a few that you know can't go wrong but might go wrong anyway. Then you fix them when they're up there. That's what their great success has been.

Now Magellan is just working spectacularly well. Some of the volcanic terrain imaged by Magellan (it's a side-looking radar, a Doppler radar that produces images by interferometry effects) shows only a few hundred meters resolution. It's going to tell us wonderful things about why this sister planet of ours has evolved so terribly differently from the Earth. It's one way perhaps of learning why the Earth didn't become like Venus, and why it might become like Venus, which is a terrifying thought. Here is more volcanic terrain, volcanic collapsed lava tubes, something they call "graph paper terrain"; nobody understands it yet. It appears to be all kinds of faults. Here are some meteor impacts. With a huge atmospheric density, it's kind of surprising that you'd get meteor impacts, but of course if you think about it, there's no water. There's nothing to erode them away. The winds aren't all that fierce, and they just sit there. So you are looking at pristine terrain probably from a few billion years ago.

Moving on outward into the planets, here is something I just found remarkable. I talked with a planetary expert, he said, "Well, we've doing this for a while, it's not that big a deal." I still find it remarkable. Remember the volcanoes on Io that Voyager saw? You can see them from the Earth. There was one right there. The arrow is pointing at one of the volcanoes at the edge of Io. You can actually study them from here. I find this just astonishing. This is high-resolution infrared imaging. The technology is just blowing apart at the seams in ground based astronomy.

Here is a microwave image of Saturn. This has been done before, but now we resume at a somewhat different wavelength. They are finding particles a couple of centimeters across in the rings. That was known, but this confirms it. But I wanted to show you two contrasting images of the planet Saturn. This is the microwave view; look at this, the Hubble view. That is just glorious. So you see, things are not all black. There is no excusing the blunders, yet the engineers and the computer experts again have been able to clean these images. This one was taken in three colors, blue, green and red, and then stacked to produce a real color image. Look at the detail up there: above the equatorial ring on the planet you can see these small turbulent storm areas. Here is the polar cap, this polar darkened region that Voyager did not study very carefully. It couldn't see it in the direction it went around. This image has a resolution of 500 miles, something like that; it's really remarkably good, far better than anything you can possibly do from the ground by half an order of magnitude or so. Beautiful, beautiful picture.

Voyager scientists have discovered a new moon around Saturn. There's the Encke division, this fine division right there at the edge of the ring. Right in the middle of it is a satellite. They have been looking for it for some time because of ripples in the Encke division. There are so many data there from these space probes that you could spend several careers just examining it over and over again.

Pluto and Charon are next. Here is a Space Telescope photograph image. That's the best picture ever taken from the ground on the left; there's the Space Telescope one on the right. So next time anybody says what about that piece of junk up there in orbit—hey, this astonished me when these came just a few days ago. I think it's incredible. The guy in the back of the room says, "Yea, we'll be doing that from the ground in about 5 to 10 years." Well yeah, sure, but you can't do it now, can you? Well no, you can't. You're going to be able to watch, determine orbital properties. We're resolving Pluto's image. We're resolving the disk here. You can't see anything on it; it's not quite that good, since it's a few pixels wide, but we are resolving the disk.

Speaking of PR, need I say more. The great comet Austin. It reminds me of Comet, well, does anybody remember Comet Kohoutek. HaHa! Another one that Johnny Carson waxed ecstatic about. Poor Kohoutek. He was a Czech astronomer at Hamburg Observatory. He found the comet while looking for planetary nebulae. He just happened to catch it on a plate and it was named after him; he didn't get any work done for a year because of the reporters knocking down the door telling him what a lousy comet he had. Here's Comet Austin; it wasn't bad. It was OK. There are a lot of fourth magnitude comets flying around. It was much fainter than everybody was expecting. It just disappeared from the skies to the intense embarrassment of the Sky and Telescope and Astronomy magazines who had been hyping it. Finally, they just had to put a lid on it because they knew what was happening.

Here is Comet Levy. Comet Levy was about the same brightness as Austin, but when it came by they figured we're not going to say anything about it. This is a Space Telescope photo. Well, it's not all that interesting actually, but it's sort of a neat historical artifact. The first photo of a comet made with the ST and you can resolve at least part of the inner coma. You can't see the core itself.

Chiron, the weird body out beyond Saturn, is acting up. It's been known to have cometary activity, but it's near perihelion and is heating up. It looks like it is a comet a hundred or so miles wide. It would be kind of fun to see that in your nighttime sky if you could get it within an A.U. of the sun.

More meteorites from the moon have been found in Antarctica. There are now about a dozen or more of them, bodies that have been blasted off the moon in large meteor impacts. That is an incredibly impressive thought that utterly dwarfs the entire nuclear arsenal of the earth. You could put all the nuclear bombs in one place, but there is no way you could blow a rock off the Earth or off the moon for that matter. You couldn't achieve escape velocity. And yet we found a lot of them in Antarctica. Moon rocks without the Apollo program. I expect you are aware there are two that we think have come from Mars. You'd hate to have that happen on the Earth. Except that we know it has happened. The dinosaur debate is heating up. There is a wonderful debate in last month's Scientific American. If you have any interest in the subject, you must look at it. It debates whether the dinosaurs were offed by a large meteor impact or by volcanic explosions. The meteor impact really does seem to be favored these days because of the iridium that you find in the layer of the Earth at the time that the dinosaurs died.

This is a radar image of an asteroid, a nearby passing asteroid. It's not a double asteroid, it's a peanut shaped job that just seems to be rotating. That doesn't seem to be terribly uncommon. The nucleus of Halley's Comet appears to be peanut shaped as well. What struck me when I looked at this Scientific American article was the picture of the Clearwater Lakes in Canada. They used this as an example of a major meteor impact, where two impacts appeared right next to one another. At the same time this radar image came out showing this peanut shaped object. Think of this coming through the atmosphere and what do you get? You wonder how often that's happened. These are a couple of miles across. If you get an asteroid two miles across hitting the Earth, something bad is going to happen. You know it has happened before and you look at the other planets and you see that it happens all the time.

Well, enough of the solar system. Moving out into the galaxy at large, let's take a look at a few stars. There have been some interesting developments in stellar astronomy. The brown dwarf controversy goes up and down and up and down. Everybody is always publishing articles: well, this is a brown dwarf. Then about six months later somebody comes along and says, no it isn't. This has been going on now for five years. Here is an example of a brown dwarf; it's the lower one. Look at the bright star at the top and then down. This one down here was a brown dwarf candidate. There were several candidates in Pleiades. They've all been knocked down. So far no one has found a brown dwarf. A brown dwarf is a star below eight hundredths of a solar mass that is too light, with not enough gravity, to raise the interior temperature high enough to produce thermonuclear reactions, so theoretically these things heat up by gravity for a while, although they shine a little bit from deuterium fusion. But that doesn't last very long and they just die. We'd like to know how many there are, and how they contribute to the mass of the galaxy, and how they contribute to the general problem of the missing mass. We haven't found any. It has really been very odd. We would expect a lot of them.

We're actually beginning to find planets around other stars. Evidence for planets comes from slight Doppler shifts. There seems to be a real gap between these and the lightest star found. We have found stars all the way down to eight hundredths of a solar mass. Below that they either disappear so fast we don't see them, or nature just doesn't make them.

This may finally be the first image of a star with actual detail on the surface, an interferometer image of Betelgeuse, which has an angular diameter of about 400ths of a second of arc. Hubble cannot quite resolve Betelgeuse. There are interferometers now in development for ground based use that will probably begin to see spots in some of these stars. We'll begin to resolve the stars with a few hundredths or maybe a few thousandth of a second of arc. These instruments are not up and working yet. But you can see a bright spot on Betelgeuse that may be real. This sort of thing came along about five years ago, but it turned out that the bright spots were just artifacts of the interferometery. It's a very difficult thing to do.

Here are rings in Orion, hydrogen rings. You can see Orion's belt up here. Orion's belt is completely encircled by a ring of hydrogen. Next is a wonderful picture made recently of the Orion Nebula showing the great filamentary structure. The photograph is massaged to show these fine, fine filaments that are actually somewhat below resolution. You can see the bright bar down there to the lower left, the one that you can easily see yourself through a small telescope. These look like shock wave phenomena all over the Orion Nebula.

There's an old picture of one of my favorite stars called R Aquarii. It's a Mira variable, one of the few that has nebulosity around it. This is actually a drawing made in the 1920's. It's still a better drawing than anybody has ever rendered photographically. The star is in the middle. It's called a symbiotic Mira and can just barely make naked-eye brightness. There's a white dwarf in orbit around a very large Mira star, and mass being thrown back and forth, and for some reason not very well understood, some of the mass is being ejected. Whether it is explosive or quiescent, nobody knows. No one has ever seen this thing go into a nova or anything like that. The reason I show it is that Space Telescope made an image right here in the middle of the thing, giving you some idea again of its capabilities. There is the central regions of R Aquarii showing great filamentary structure in the middle. The black spot in the center is the star. The star oversaturates the CCD and then it just turns black.

Here is a standard photograph of Omega Centauri, the greatest of all globular clusters. A truly spectacular sight by the way. It's well worth it, if you ever get into the South, to try to see it. It's fourth magnitude, so you can see it with the naked eye. Even in binoculars it's wonderful. In a small telescope, you're just not going to be able to believe it. You're going to go knocking on people's doors to get them out to see it. We don't know much about the cores of globular clusters because the star density is so enormously high. The Space Telescope made an image of the middle of M-14 in Ophiucus. I didn't have a picture of M-14, so I show you Omega Centauri instead. There's a ground based photo on the left. Look at the one on the right! Look at the resolution. This is in the core of Messier 14. We're now going to start understanding globular clusters better, which is a very important thing to do from the point of view of stellar evolution, because these are the first things ever born in the Galaxy. These things have x-ray burstsers, they've got pulsars, they've got all kinds of crazy things in them. And we can't look into the core optically very well at all, and this is going to start doing it for us.

This is just a piece of trivium. The large blob is M87 in the Virgo Cloud. The arrow is pointing to the most distant star in our own galaxy about 150,000 light years away. Nobody really cares, it's just sort of a record for a star. It does show, however, how far stars are, how far spread out the galaxy really is. The standard rubric is 100,000 light years across, we're 30,000 light years from the center, and so on. But of course, the galaxy doesn't just stop, it just keeps going and going. Sort of like the energizer bunny. The star density gets less and less, and even at a distance of 150,000 light years, there's a star still confined to the gravitational field of the galaxy. It must be quite a sight if you're way, way out there looking back on us.

The Magellanic Cloud is next, with 30 Doradus at the upper left. You know if you put that thing where the Orion Nebula is now, it would fill the constellation of Orion and would light up much of the sky. It's called a giant HII region. Our galaxy doesn't have any. They seem to be confined to these loose open spirals and some of the irregulars. This is sort of a loose barred spiral. You find them in M33, but not in our Galaxy. You find them where star formation is going on.

In the middle of 30 Doradus, the Tarantula Nebula, is a star called R136a, not a very glamorous title for a remarkable object, one that at one time was thought to be a superstar of about a thousand solar masses. There were a number of papers published on this. Then the interferometer people got onto it and said, "Well, we're resolving the superstar into more than one star." This is a ground-based photograph of R136a, and you can see that it has structure. It's not just one star. This is very important in an evolutionary sense because we'd like to know what the largest stars in the galaxy are. Theoretically they should be around 100 or 125 solar masses. Above that the luminosity is so great that it produces such a strong wind that the star simply limits itself, or tears itself apart. So if you've got a 1000 solar mass star, it should just go poof and it's gone; it just blows its outer layers away. There shouldn't be any 1000 solar mass stars. The discovery that there might be one was really remarkable. But it's not, it's a cluster. Here is the Space Telescope image, and then the computer generated Space Telescope image. It almost looks like a little globular cluster. Well, a very tight galactic cluster; they're almost all O-stars, and they are just packed in together. Can you imagine what that will look like when the supernovae start going off? They do that in the Magellanic Clouds.

This is the region around Supernova 1987a. Look at all the bubbles. Those are mostly windblown bubbles, blown either by hot O-stars or by supernovae. You can see huge bubbles in the large Magellanic Cloud with star formation on the edges. Then the super novae pop off on the edge and produces more bubbles. So you get nests of bubbles in the Magellanic Clouds. It's an incredibly complex region. The light echoes around the supernova have been increasingly observed over the last year. These are carreid by light from the supernova itself bouncing off nearby gas clouds and producing these circular rings.

The Space Telescope image of SN1987a shows this little ring around it. The ring actually can be seen from the ground. It was discovered from the ground but the resolution here is much better. The ring is apparently the result of previous mass loss. These massive stars lose a great deal of mass before they explode. They may lose half of their mass before they explode because they are so very luminous. So they're immersed within their own effluvia, and then when the supernova goes off, they compress the previous zone of mass loss and you get a little ring that looks very much like a planetary nebula. The planetaries are formed similarly by previous mass loss being swept up by the hot wind from the exposed core of the star, the white dwarf. The energetics involved, of course, are terribly, terribly different.

How about a new galaxy? Every astronomer everywhere has had the experience of somebody, "Have you ever discovered a new star?" Well, of course, I can look at a Palomar Sky Survey plate, point to some little dot, and say, "Ha, I discovered that star, we'll call it after me." There's so many, who cares? The same is true of galaxies, except this is a little unusual. It's a dwarf galaxy, another companion of our own Milky Way galaxy. You can't even see it. The author had to put on contours so that you can see where the stars in the galaxy are. I can't see a galaxy there to save my life. You're not going to see this through your three inch, that's for sure. There are a lot of these things, we've got a couple dozen or so of these little dwarfs all around, just sort of flies around a hamburger. What an awful analogy; you haven't even had breakfast yet.

NGC 7457 is a fairly well known elliptical galaxy. Here is the Space Telescope image. Look at the resolution on the right! I've seen ground based images of the companions of M31 that approach that, but really nothing like this. Look, you can see the structure around the edge of the galaxy. Those are almost all giant stars. You're actually resolving the giant branch here, and as they say, technically it's just zillions of stars, they're all over the place. You-know-who can become famous for billions, maybe I can become famous for zillions. In a computer-massaged view of it, you can see the nucleus, a very compact zone where the star density is 30,000 times greater than it is in our own local Milky Way. Now think of supernovae going off in there all the time at a density 30,000 times local. You may start generating the central engine for some of the bizarre effects that you associated with galaxies, including black holes. As the stars interact with one another, all the mass falls to the center, and the central object becomes bigger and bigger. Maybe you generate a black hole that way, just like you generate giant elliptical galaxies at the centers of major clusters, because the galaxies collide and all the sweepings drop to the center of the gravitational well. M87 then just gets bigger and bigger as it effectively eats all the other galaxies in the cluster.

NGC 1064 is a fairly large galaxy. Here's a 1912 photograph made with the 60-inch telescope on Mt. Wilson to show you the contrast of technologies. The Space Telescope looked into the center of this spiral and saw HII regions, an incredible number of them. The red bar is one arc second. Look at the resolution; it's just wonderful. So, there's going to be some good, good science coming out of this thing. Unfortunately, only at 20% of the rate they expected. Still, the science is going to be excellent. You're actually resolving things in this galaxy that are maybe only 15-20 light years across.

Parkes 0521-36 is another active galaxy; this is the ground based picture showing a jet. It is reminiscent of the M87 jet, the giant elliptical in the middle of the Virgo Cloud. The jet in M87 goes all the way to the edge of the galaxy and beyond. In fact some of these jets are the largest structures in the universe, utterly dwarfing the galaxy inside. It's a very common phenomenon. Somewhere in the middle of that white blob in the center is the central engine. The textbooks call them that now because they don't know what they are. If you want to go out on a limb, you say it's a black hole that is pouring material out of its poles. You get one jet coming out one way and one the other. We see the one that coming toward us; the other is being hidden by dust or whatever. The Space Telescope view: it's not a lot better than the ground based actually, but it's a slide from the Space Telescope and I want to show it to you anyway.

Now for the most distant galaxy. We've have another a new record for galaxies. I think this comes in at something like 12 billion light years, depending upon which model of the Universe you want to assume. There are always records coming along; I find this much more remarkable: through an enormous amount of work and almost hundreds of hours of integration, astronomers have been able to integrate to the absolute depths. You're looking at galaxies here at 28th magnitude, which I think is a record from the ground. The Space Telescope is only expected to go to 30th. What do you see? This is two minutes of arc across and every one of those images is a galaxy. There are hundreds of them in this little bitty area. That extrapolates out to literally billions, many billions of galaxies over the entire sky. What we're looking at is galaxies that may actually be at the fringe of the observable universe, maybe 12-15 billion light years away. It is just an absolutely stunning image. These are called faint blue galaxies. You can see some of the bluest ones scattered there in the distant background.

This is the Einstein Cross. It is a quasar lensing phenomenon. This has been one of the more interesting areas in extragalactic astronomy. There's one quasar back there. There's a galaxy right here in the middle, and surrounding it are four images of the same quasar. As the light passes the galaxy, it gets lensed by the galaxy's gravitational field. Usually these things come in pairs, but the quasar aligns with the galaxy almost perfectly, and theoretically you expect to get a cross like this, and it's the only example known of something close to the perfect image. Remarkably, one of these, and I can't remember which one, suddenly brightened and then dimmed again. The theoretical explanation was that a star within the galaxy passed in front of the quasar within a millionth of a second of arc or less and itself imaged the distant quasar. In fact theoretically they think it even couldn't have been a star, it had to be so small that it was probably a planet. Well, it's a little outré as they say, but it was the only theoretical explanation that they had. Wouldn't Newton loved to have seen this! Gravitational effects just gone berserk. Wonderful picture.

The Hubble Law controversy rages onward; I don't think it will ever die. We talk about our ability to learn about the universe and then the astronomers on the west coast say, "Yeah, the Hubble constant is fifty kilometers per second per megaparsec." The astronomers of Harvard say, "Na, it isn't, it's a hundred." They can't agree to within a factor of two. A hundred kilometers per second per megaparsec gives you an age of the universe of about 10 billion years, which is less than the age of the globular clusters as determined by the stellar evolution people. That's not a good number; there's something wrong someplace.

There is now a new way of determining the Hubble constant using my favorite objects, the planetary nebulae. These little devils are everywhere. This is an image of M81 in Ursa Major, and here you see an image of a planetary nebula. We're imaging hundreds and hundreds of these planetaries, which are just gas clouds ejected by old stars just before they become white dwarfs. In fact, I've just got to tell you that I'm going out next week to observe the spectra of some 175 planetary nebulae in M31. We will use a multi-fiber-feed spectrograph where you take 50 fibers and put them on 50 planetaries or stars at one time. They feed into a CCD and you get 50 spectra at a shot, as long as your field of view is fairly small. It turns out that there is a maximum limit to the luminosities of planetaries and the brightest ones within a galaxy give you an excellent standard candle for determining galaxy distances. Jacoby and his gang at Kitt Peak have found a Hubble constant that falls somewhere between 75 and 100 excluding Sandage's 50, rather definitely excluding it.

The problem with the Hubble constant is not so much with the distances as with the determination of the velocities of the cluster at large. Because of the random motions within the cluster it is very difficult actually to get mean cluster velocities. That's really the limiting factor right now.

The lower limit to the Hubble constant, which is here 75 kilometers per second per megaparsec, gives you an age of the universe of 13 billion years and is in line the globular clusters. So actually that may be the best number to use, giving us an age of the galaxy of about 13 billion years. Don't quote me; it will probably change next year.

The Great Attractor now has some more support. In the

Hydra-Centaurus direction there is an enormous gravitational attraction we can't see that causes a streaming motion of the nearby galaxies. Galaxies seem to be moving in this direction, over and above the Hubble flow. This is a graph of the Hubble flow in the galaxies in the direction of the Great Attractor. This is in front of it, and this is in back of it. So it looks like galaxies are falling toward it in the other direction, which gives you a lot of confidence that the Great Attractor is out there. We still don't know what it is, whether it's a dense cluster of galaxies behind dust or what. There's a lot of "missing stuff" out there.

Here is NGC1310 on the upper right. There is an arrow pointing at nothing called ALF. Not that ALF. The radio image of Fornax A is in the middle. You can look at the polarization of the light in the radio image, and what you'll see in the next slide is that NGC1310, on the upper right, has depolarized the radio radiation, implying that there is a lot of matter in it that you can't see. It is perhaps the so-called missing, or dark, matter. There's another dark patch right where ALF is; you can't see anything optically at all. Here's the image and you can see the dark patch produced by NGC1310 right here and here's ALF. ALF, by the way, means "ant-like-feature." You've got to hand it to these astronomers. They come up with just the darndest names. There's some matter here that is depolarizing the radio image and we don't know what it is. There is missing mass everywhere. You see it in the Galaxy's rotation curve. You see it in the velocities within clusters of galaxies, which always give you cluster masses of that are an order of magnitude greater than you can account for in terms of the number of stars in the galaxy. Is that enough mass to close the universe from the Big Bang? We don't know; we've been looking for the missing mass for ages. Well, it's called missing mass for a really really good reason.

Galaxies, galaxies everywhere. This is a computer reconstruction of about 50 million galaxies around the south galactic pole. It is absolutely awesome to think of the number of them that there are out there, then you think that each one has got a hundred billion stars in it. The amount of mass in the universe is staggering. Look at all the possibility for planets. What this shows is the filamentary structure of the universe. You can see bubbles and voids and strings and streams of galaxies. It has a very frothy, very irregular, structure. The Universe is not uniform. It's very very far from it. That has been the stunning surprise . We have gotten distances by looking at literally thousands upon thousands of Doppler shifts, and we see vast voids where there are no galaxies. This is a kind of map of the local region. The area up here where there aren't any galaxies is of course just the disk, the plane of our own galaxy, the zone of avoidance where you can't see any. One of the great discoveries was this feature over here of an enormous structure, one that extends for perhaps a billion light years, called the Great Wall. You can see these long structures that may or may not be real. There is some criticism of it. It was very popular in the 1930's to talk about star streams. You look at a photograph and the eye picks out strings of stars, but they're not real. We don't know whether these things are real or not. Nevertheless, you can see great structure in the universe.

Why should you see great structure in the universe? This is one of the most profound questions that has been raised in the last decade. Why should you see such great structure when the 3 degree background radiation is absolutely uniform? We don't know. You should see deviations from the cosmic background radiation. It is 2.735 degrees Kelvin no matter which direction you look, barring the Doppler Effect caused by the motion of our own galaxy. Why should the Big Bang be so terribly uniform? The background radiation is so uniform and the number and distribution of galaxies is so absolutely irregular. It doesn't make sense. It's causing some people to start thinking that maybe the Big Bang is a fiction, maybe it's not real, maybe it didn't happen. Maybe something else happened that we don't even begin to understand. That's not the majority viewpoint by the way. But it is a creeping doubt.

This is another result by COBE. The picture shows the results from three infrared bands. These are all-sky views of the cosmic background radiation. The colors show the dipole nature of the cosmic background radiation caused by Doppler effects from the motion of our own galaxy against the local Hubble flow. Here is a zone of approach and here is a zone of recession. But it's a perfect dipole, so you can explain it perfectly just by the motion of our own system. You take that out and the background radiation is absolutely uniform.

Over the years there has been an enormous controversy going on, sometimes known as the Arp controversy from Halton Arp, who was an astronomer at Palomar. He found what he thought were a lot of coincidences between two galaxies having grossly different Doppler shifts. The idea is that you have two galaxies that are obviously interacting with one another, and so they must be at the same distance. Why then are the Doppler shifts different? This brings up the possibility that redshifts of galaxies are produced by something other than recession. What it would be caused by we don't know. There have been some rather bizarre ideas as how that can happen, but nobody really understands it. Arp has gone on to document hundreds of cases of these interacting galaxies and there is an example of it. Not the big one, but this little elliptical down here is another galaxy and the two redshifts differ by a factor of 10. There was some evidence that the quasar, which is another factor of 10 off, was involved and enmeshed with the system. This is mostly just for illustration. The astronomer who took this image claimed that in fact the image was so good that you could see that it was just a chance coincidence.

Arp got into a great deal of difficulty. The astronomers at Palomar and the head of the TAC (telescope allocation committee) told him he couldn't use the 200-inch anymore because his ideas were too strange. You've got to be awfully, awfully careful about that. Palomar has been under attack because of it, because they found that a non-mainstream scientific result wasn't good enough to support. I think whether Arp is right or not, it was a dreadful thing to do. Arp took off, is now living in Switzerland, and is still producing this kind of work. It's not mainstream and most astronomers think that it's wrong because you've got so many galaxies. Remember that deep image that we showed a little while ago. The chances for coincidence are terribly high, that he has not yet made his case statistically.

Yet the general feeling out there is that there may be still something wrong. There's a minority of astronomers that are beginning to feel, including Geoffrey Burbidge, who used to be head of Kitt Peak, that maybe the Big Bang didn't occur. The Steady State Universe is starting to make a rise again from the ashes. Amazing. Well of course, Hoyle is part of this; he never let it die. Please, this is very, very minority opinion. Yet you can't discount minority opinions. Not in science, because many times they have turned out to be right. And I expect we would be truly utterly astonished if we really knew what was going on out there. We are in a very primitive state in terms of our understanding of galaxies and the Universe at large. Heck, we can't even seem to detect more than 10% of the matter that's out there.

We come back now from the great distances to one of the most marvelous machines ever made, Voyager 2. That is not to discount Voyager 1, but it got shot out from Saturn and has been sort of forgotten in the public mind. When Voyager 2 passed Neptune—wait, I want to put this back into context. We've been looking at zillions of galaxies, and then you tend to forget about the Earth. You tend to forget about the fact that the Earth is important too. You have people who will tell you, you have all had this question, "Don't you feel insignificant?" We're so small and we're so just off to one side of an anonymous galaxy and what are we after all? It just boggles the mind. I think I'll just go home and watch Donahue or something. The answer is, "No, you're not insignificant. You can understand it!" That is not insignificant; you can look at it, and you can understand it. In a very, very real sense, all of this great cosmic engine, the galaxies and our own galaxy, has created the Earth. Without all of that, the Earth would not exist. It does not exist in a vacuum. This is your home. The whole thing is all of our home. The Universe had a part in the creation of our Galaxy, and all the stars in our galaxy have had a part in creating the sun, and in creating the planets. The sun has got a piece of practically every star that existed, that is, every star that existed and died before the Sun was created.

Voyager was able to put this in a little bit of perspective, because it got out beyond the orbit of Neptune. In a long series of images, they looked back at our little planet. It partly destroyed the camera because it had to look too close to the sun, but it didn't matter any more since there were no planets, at least that we know of, for it to look at. There's the array. You can't show the whole thing. If you showed the whole panorama you wouldn't see the planets anymore. But there we are: Venus, Earth, Jupiter, on the top, Saturn, Uranus, Neptune. Uranus and Neptune aren't really shaped like that, but the exposures were so long that they moved during the imaging. Right up there in the upper middle is us, as viewed from well beyond the orbit of Neptune. We fill one pixel; we're square on this picture. But we're blue! We're blue! Who's blue? Neptune's blue. Methane. We're blue because of water. We're from all of that out there in the Universe. It's all part of one system. It's a spectacular universe we live in and maybe, maybe, someday, we'll begin to understand it. Thank you.