UATP: NEW HORIZONS IN UNDERGRADUATE PHYSICS EDUCATION

ROGER BLANDFORD
STANFORD UNIVERSITY

C: I am extremely happy that we will hear from Roger Blandford. Roger is a very well known astronomer. He has also achieved a certain amount of renown by a level of public service that is awesome. And it includes chairing the Decadal Survey of the NRC, sponsored by the National Academy of Sciences, that produced this wonderful program of researches of great significance that should guide the community for the next decade. He has also had the jarring experience of having a beautiful program laid out with a budget that is conservatively drawn, only to find that with the new budget environment that the conservative budget is actually radical. He is dealing with some of that now by flying back and forth to Washington — which is the life of some one at Stanford University. Roger is also the director of KIPAC, the Kavli Institute for Particle Astrophysics and Cosmology there.

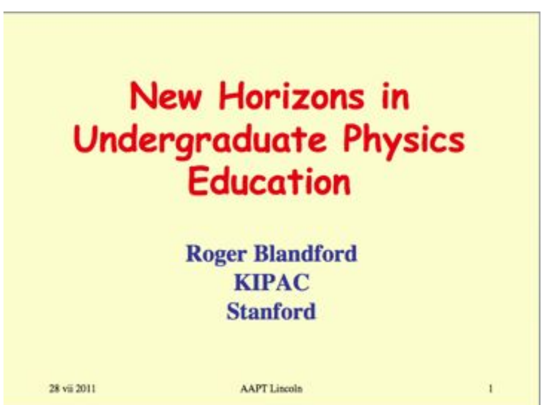


FIGURE 1

He is a person very much involved in presenting astronomy to a wide variety of audiences. He has been a big help to those of us who have been trying to get rolling this idea of using astronomy to teach physics. He has been an advisor to the group who have been planning it and are planning the Gordon Research Conference next year. I think he's gone the extra mile — many extra miles — to be here, and I really appreciate it, Roger.

Roger is going to be our official keynote speaker opening this occasion — depending on which time reference frame you are in.

B: I actually know where I am. I apologize for being late. I certainly went the extra mile; I walked all around the campus looking for this meeting. And I've been sent to all four corners of it, but eventually I found it. So I'm very glad to be here.

I feel a bit of a fraud here, because unlike David and Barbara I'm not a well known educator. Although I've been teaching for 44 years, I regard myself as an indifferent lecturer and teacher and I think my students would probably agree. So I think I should be learning from you rather than the other way around. But if I can stimulate some discussion, I perhaps will have done some good here.

The further apology is that I ought to have coordinated with my colleagues David and Barbara, and I have not done so, and there is a certain amount of overlap, but I may have a slightly different take from them. Ultimately want to get to what I was asked

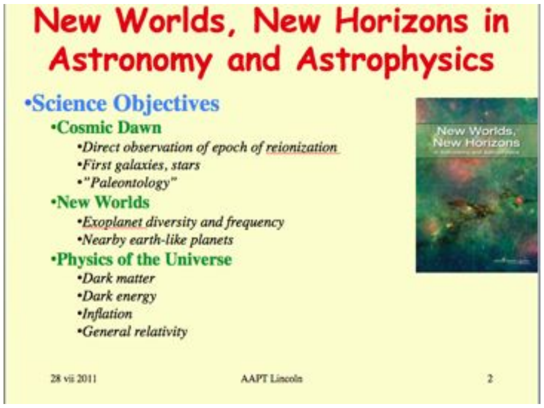


FIGURE 2. New Worlds, New Horizons

to discuss: how to use the material of modern astronomy and astrophysics to communicate physics ideas to undergraduate majors, concentrating on the first and second years.

Charles mentioned *New Worlds, New Horizons* and this is the cover of the report that we created. I am certainly not going to go through it here. I've given 25 talks on it, and I don't want to give 26. But I will just lift the three science themes that emerged from it. And, despite budgetary problems in the United States, these probably still are very good guesses as to where the action is going to be and what your students are going to be hearing about by reading popular articles and so on.

The first is what we call "Cosmic Dawn" or, more technically, the epoch of reionization, when the atoms in the expanding Universe then separated again. (I'm not quite sure why it's called reionization; they weren't ionized before that, but there it is.) It's soon after the time when the first galaxies and stars were formed. We are starting to glimpse that era using astronomical telescopes. We're also seeing the fossil relics of that time in very, very old stars. Understanding what actually happened and when and where is one of the great challenges of contemporary astronomy, astrophysics, and cosmology.

The second growth area is what we called "New Worlds," but it's really concerned with the discovery of exoplanets big time. Now I'll come to say a bit more about this. But the extraordinary thing is how diverse they are, and how common they are. My own view is that we're actually at the start of this epoch of discovery. It's really quite amazing how developments in techniques that have been around forever but not very efficiently used and all of them very inexpensive have led to this great flowering of a completely new field that's attracted a lot of young people. Many of the best graduate students out of astronomy and astrophysics departments are headed for this area. It's a very different type of science from the cosmology and high energy astrophysics that attracted their predecessors. It involves chemistry, biology at some level, and certainly orbital celestial mechanics in a very new guise.

And then third, we're seeing the pursuit of doing physics where we're using the Universe as a giant laboratory, not one where we hope to perform experiments but one where we allow the Universe to perform the experiments for us, and we take the data. And the big topics here, of course, are dark matter and dark energy. I'll say a little about this; inflation I will say not so much about, because I think it's a little bit hard; but I can talk about general relativity which I think you perhaps can do something about for this target group of the first two years of undergraduates taking physics.

Images are one of the great attractions of astronomy. You've just seen this spectacularly demonstrated by David, and you will

FIGURE 3. The power of the image

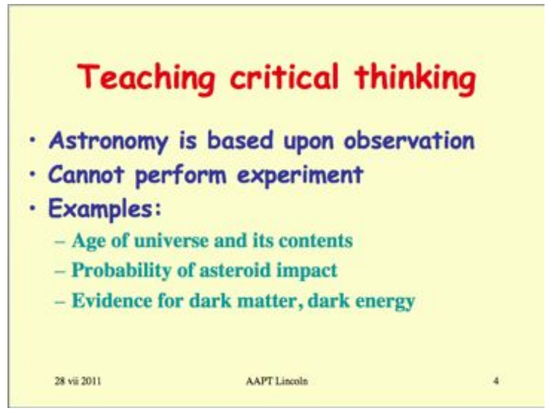


FIGURE 4

see it again, I think, by Barbara. I'm not going to belabor this, but here is a set of images from all over the place. Astronomy's images catch the public imagination. The image is, if you will, a sort of loss leader for getting people interested in science — and astronomy has the great advantage that images are not only an essential part of the topics that we're dealing with, but the images we create with our telescopes are riveting, and they bring people in. We should not be ashamed of that; we should use that all the time. I think it's the case that a quarter of a million students do some form of astronomy. This is the science that they get.

Astronomy is the most popular science to take in college, so we have a golden opportunity to teach something that is in somewhat short supply at the moment — which is critical thinking. Now it's not the same as teaching experimental science in the laboratory or many other types of rational thinking. But it is more relevant than just astronomy, because a lot of it is based on observation. Increasingly one is dealing with social issues or political issues where you can't perform great experiments. You can't take some sort of medium sized country and send in a lot of white-coated economists to find out what would happen if we had no taxes. Or what would happen if we had ten times the taxes? You don't do that sort of thing. Or climate change: I wonder what would happen if we injected vast quantities of aerosols into the atmosphere? It's a good experiment to perform. Life as we know it may end, but it's a good experiment to perform. You don't do that sort of thing. So you are doing much more observational, inferential things. For example to pick three science examples: What is the age of Universe and its contents? What is the probability of an asteroid impacting Earth? What is the evidence for dark matter and dark energy? We can use these as case studies of how astronomers attack this type of problem with a methodology which might have some relevance to other problems that are way outside of astronomy — methodologies you use where you really want to know "What will happen if . . . ?" Then you have to assemble the evidence that you have without being able to perform the experiment that one part of your brain might like to carry out.

Another thing to teach is the difference between engineering and physics. When one

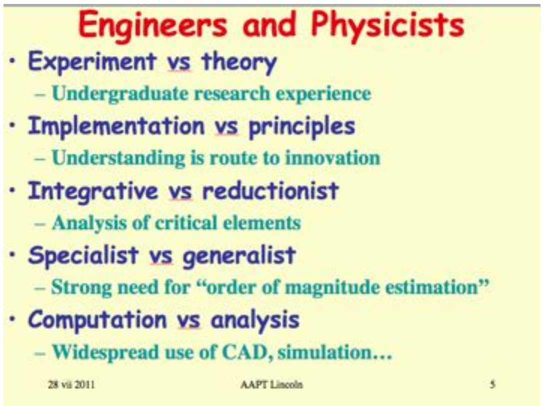


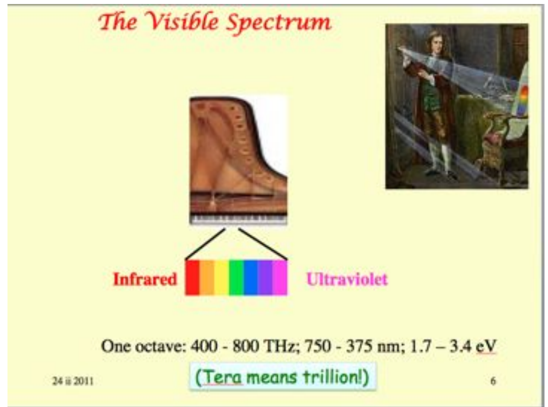
FIGURE 5

is teaching the first two years or so of astronomy, one is often teaching engineers as well as pure physicists. And the mind set of an engineer, as a professional or a student, is already somewhat divergent from our view of what physicists are. Not in a bad way — my own two sons are both professional engineers, and they're very suspicious of physicists, of course. (I certainly brought them up that way.) I would say that what engineers are more concerned with is rather different than the sort of traditional concerns of a physics professor. You might say the engineer vs. the physicist is the experimentalist vs. the theorist. Physicists do theory. And the engineer doesn't really care whether the laws apply or not; he just wants to make something work. Well, that may have some validity, but I think the really integrating experience here — this is where physicists and engineers can get on — is in the undergraduate research experience. It's not doing the carefully constructed experiment in the first year physics laboratory. It's doing the discovery of either research or development in some undergraduate research experience where when you're dealing with it you don't know what you're doing, and the normal state of grace is that it doesn't work and the person who has been giving you advice about it doesn't know what they were talking about. This is an integrating experience for engineers and physicists. The physicist might have a view of engineers that would say that all they're doing is looking it up somewhere in some table and they don't care about it all. But that's not good; I think any engineer will say that to you. You've got to understand at a very fundamental level, because that is more often than not, the pathway to innovation nowadays. You might be a fellow who has stumbled upon something by pure chance and were awake enough to notice, but more often than not, it's understanding that is the road to innovation. Innovation is what a lot of engineering should be about.

There's another sort of axis here which is the integrative approach versus the reductionist approach. Physicists — some types of physicists — are famously categorized as being reductionists; they are committed to what is called "nothing but-ery." They're always trying to reduce experience to its most fundamental elements. Now we all know, as physicists, that is not a fair characterization of even modern theoretical physics, because a lot of it is many-body, is collective and so on. And so it is not reductionist. And for engineers, it is certainly the system that is very often the important thing. And I think that should inform our teaching.

Another sort of axis important to think about is specialism vs. generalism. Engineers often are quite specialized. They will decide — as one of my sons did — I'm going to be a mechanical engineer so I will do what mechanical engineers do. To some extent that's true, but if you look at an engineer trying to make something work, trying to build something, it's the failures that are important and interesting. And more often than not when things go wrong — which happens a lot, of course — it's because there was something that was not in the rule book, not in the pathway, but something outside she didn't know about. And here I think it is very important when teaching engineers — I've certainly been told this a lot by engineers, and it's something that physicists are doing more of now — to understand back-of-envelope order-of-magnitude analysis so that you can make quick estimates that will tell you "I don't have to worry about that"; or,"whoops, I didn't really expect that to be important, but if I believe this estimate, it's a 10% effect so I'd better go back and look at this in more detail. I'd better learn a bit more about it." The failure to carry out that sort of analysis is one of the two failure modes that happen quite often. (The other, of course, is the interface between two groups that aren't talking to one another.)

And then finally we need to be aware of how important computation is vis-á-vis analysis. Again the traditional physicist does elegant calculations using nineteenth century applied mathematics. For an engineer a lot of that has gone out the window, because even more than physicists, they are relying upon computer aided design, numerical simulation and the rest. This is the professional line nowadays. And yet analysis does have an importance, and I think we have the responsibility to keep that there, not at the level of the very intricate problems that people used to solve because they didn't have computers, but at the level of being able to convey understanding by having a good suite of simple problems that represent the sort of lingua franca of people trained in physics and engineering, so that everybody has done that problem once before, and they know it, and it provides a reference point for complicated analysis that might involve finite difference numerical simulation or whatever.



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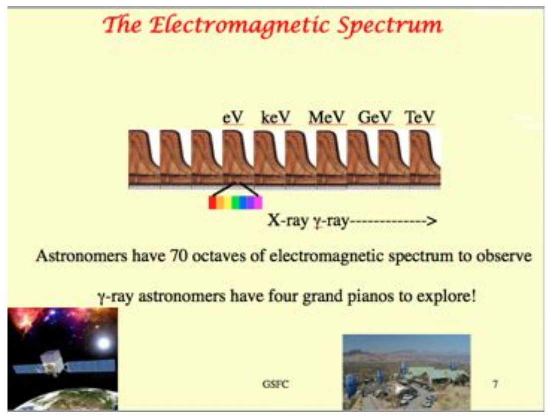
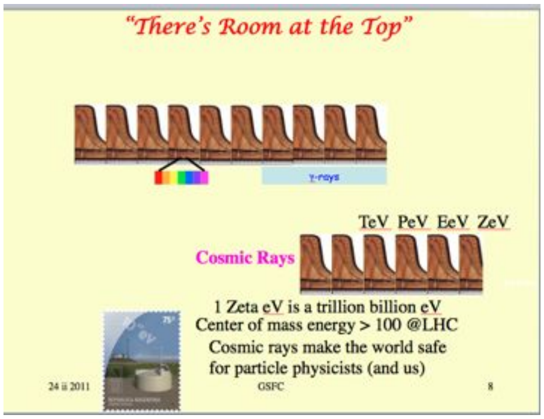


FIGURE 7

I probably don't need to show you these pictures, because David has made the point very clearly: The visible spectrum is just one octave. Many of my colleagues are optical astronomers and they have, I think, a very jumped up view of their own importance; I'm sort of a gamma-ray astronomer



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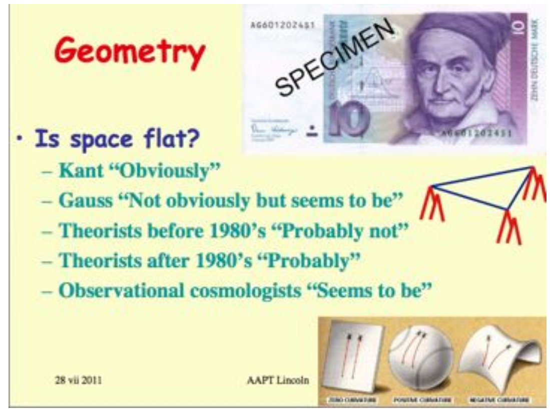

FIGURE 10

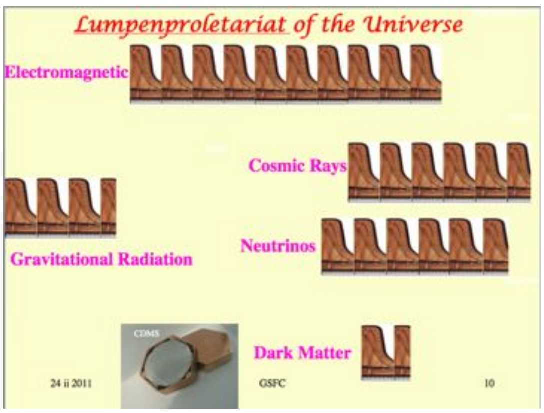

FIGURE 9

some of the time, and we have four grand pianos worth for that one octave of the optical astronomers. And of course if you go to the other part of the spectrum, if you go to the cosmic rays — at the moment they go up to zetaelectronvolts (ZeV) — that's way beyond the electromagnetic spectrum that we're used to in astronomy. Then there are neutrinos, dark matter, and gravitational radiation. We have these four non-electromagnetic channels too with another seventy octaves of the spectrum there. Opening this up using technology is the reason why there's been this explosion in astrophysics over the last sixty years.

Okay, so let's talk about some of the topics that come up. I might be riding some hobby horses here, for which I apologize, but let's discuss some of the concepts that may arise and where astronomy, astrophysics, cosmology, and so on might have something to contribute to getting the ideas across to a physics student who is trying to learn the subject.

I have some background in relativity so geometry is always very important to me. The question involves Euclid's fifth postulate: "Is space actually flat?" To Kant this was an a priori truth; to Gauss it was not a truth because he knew about non-Euclidean geometry. He performed the experiment — there it is. He did the experiment the way we do it; he was observatory director at that time so he just sent other people off to see if the angles in the triangle added up to 180 degrees. It's a good question, and within the errors they did.

If you ask about the Universe at large, as investigated by cosmologists, I would think that most theorists before the 1980s had the suspicion that the Universe was not flat and that you had to use non-Euclidean geometry

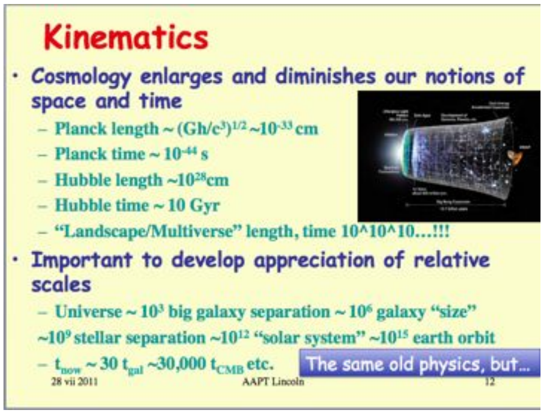

FIGURE 11

to describe the space of the Universe. And after the 1980s and the postulation of the theory of inflation, there was a reason — not actually accepted by all theorists, but by most, I would say — for believing that the Universe has a mechanism for flattening out the Universe. And so a lot of theorists would have then said that the Universe is flat and that the angles in a big cosmic triangle would add up to 180 degrees. But, you know, observers were rightly suspicious of all these argument and went up and to all intents and purposes used the microwave background to measure it, and to a fraction of a percent we know it appears to be flat. So this is something that I think is settled; it is not too soon in an undergraduate physics course to explain just as you do in mathematics that this flatness is a truth which we have some basis for believing, and the world did not obviously have to be like this.

Next, one thinks about kinematics. Again, when teaching, you get students from high school who are well armed with techniques for solving problems in dynamics up to a point. But it's very important to go back and re-examine the kinematic foundations of what you're doing; what you mean by time and space and length and dimension and so on. And it's not just a question of the idea of what is meant by length, and why time is different (or is it?). It's really expanding the student's view of these physical quantities. In astronomy they have probably heard of Planck's constant in high school and by dimensional analysis you can create the Planck length — 10^{-33} cm or thereabouts; and the Planck time related to it obviously by the speed of light in the denominator — 10^{-44} s. Students can be impressed by this.

On the other end of the scale if we just look at the characteristic size of the observed Universe, the Hubble length is 10^{28} cm; the characteristic time is 10 Gy. We're clearly doing order-of-magnitude analysis here. They have also read in *Scientific American* or other popular articles about the landscape and the multiverse, and how we live in an eternal Universe, continually budding off new forms and so on. And the characteristic range of scales is 10 to the 10 to the 10 to the 10 to the 10, . . . , I jest. However, just understanding these relative scales is important. From the point of view of astronomy we now are at the point where we can communicate — I hope — a familiarity with the observed Universe.

And just as you can say that you know I'm 10 billion atoms tall or so, and an atom is the same size as 10^5 protons stacked up one on the other, you can develop an appreciation of the relative length scales involved. So in various round numbers you would like to communicate, the Universe is roughly a thousand times the separation of big galaxies, and a million times the size of a galaxy, and about a billion times the separation of stars, and about 10^{12} times the size of a solar system. (I didn't know how big our solar system is, so I took the geometrical mean of the Kuiper Belt and the Oort Cloud.) And then about 10^{15} times the Earth's orbit. I'm

FIGURE 12

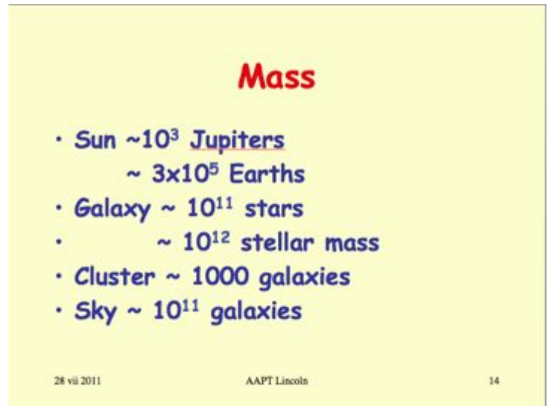

FIGURE 13

not saying this is a quiz in which you have to write down these numbers, but simply supply some appreciation that the Universe .... in terms of millions, billions, trillions....

In terms of time: The age of the Universe is 130 times the age when the first stars appeared, 30,000 times the time when we first see the microwave background. This sort of relative thinking is important. So far as we can tell the physics we divine from laboratory experiments, from looking at textbooks, or whatever applies throughout these different scales of length and time. There are some people who question what I have said, buy the transitions for atomic lines, or their ratios, are the same in a quasar as they are in some incandescent bulb in the laboratory.

Speeds: Again this is just relative, just trying to put things in perspective. The sprinter there goes about 10 m/s; the speed of sound is about 300 m/s; a star goes around a galaxy — Andromeda, for example — at about 300 km/s; dark matter particles too; light goes at 300 Mm/s. And the ultra high energy cosmic rays — this is one I like — high energy cosmic ray particles with ZeV energies (I'll return to this maybe at the end) lag a photon by a fm/s — a femtometer (or Fermi) per second — or a couple of kilometers per Hubble time; so that a cosmic ray coming from the other side of the Universe would lag a photon by a kilometer.

Astronomy is very good for conveying understanding of relative sizes. This may be just kinematics, but it gives a sense of magnitudes that is good conceptually.

Masses: Again just relative sizes — you don't want this to be like those dreadful middle school science tests where you have to recite the geologic eras and so on, or the periodic table of the elements. We don't want that. But you want students to develop some appreciation, some familiarity with the objects that astronomy studies. You know: the mass of the Sun is a thousand Jupiters, a million Earths; a galaxy's a hundred billion stars; the amount of dark matter is nearly 10 times that of stellar matter in terms of mass. There are clusters of the order of a thousand galaxies drawn together by gravity. Only a few of these galaxies can be seen with the naked eye, but seen through telescopes, the sky has countless numbers of points of light that are galaxies; some of these are pretty feeble; we'd be rather ashamed of them if they were our relatives. But there are over a

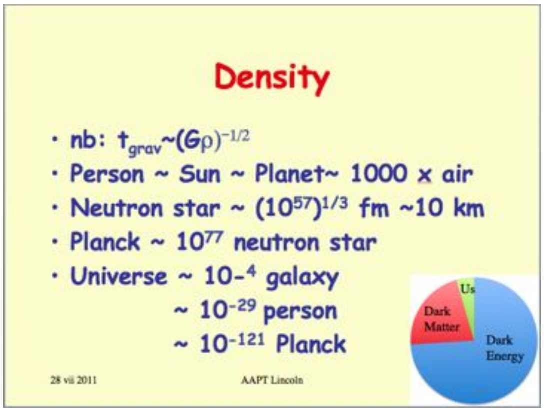

FIGURE 14

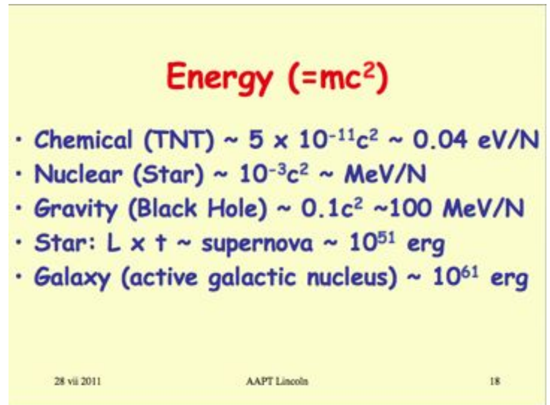

FIGURE 15

hundred billion on the sky; you can just add them up.

Now here's something central to astrophysics — this little formula. It is that the characteristic gravitational time scale is $1/\sqrt{G\rho}$ one over the square root of Newton's constant times the characteristic density.

This comes up all the time. The density is the same for a (wet) person, for the Sun, for a planet — roughly about 1 g/cm^3 (actually it's a bit more). If you go to a dense structure in astronomy such as a neutron star, its mass is 10^{33} g. Because a proton or a nucleon is 10^{-24} g, there are roughly 10^{57} nucleons in a neutron star; the cube root of that is 10^{19}; multiply that by a fermi (femtometer or fm) — the size of a nucleon, and you get 10 km. Another density is the Planck density, the one that you get from the Planck mass and time and so on, is 10^{77} times the density of a neutron star. So ones mind is certainly blown away by that. The Universe has a density of about 10^{-4} times that of a galaxy. 10^{-29} of a person; or 10^{-121} of the Planck density.

And you see here in the lower right corner something worth driving home — an idea that is very common, almost becoming part of culture (almost, but not quite): The baryonic matter that we and the things that we know about and focus on is 4.5% of the mean density of the Universe. (Obviously locally we're doing a bit better than that.) The dark matter — two mysterious components; one is the dark matter — is about 20% and then the remainder, almost three quarters in terms of mass energy density is the dark energy. These are two new distinct components that have been identified by cosmologists. This pie chart sometimes helps to get the point across.

Energies: Astronomers like to watch things blow up. Maybe they like to blow them up too, especially if they're rocketeers. Anyway the range of energies is good to get across: Chemical energy can be fearsomely impressive - with dynamite you can take out full size masses. Using the bomb maker's prescription, it is .04 eV/nucleon or $5\times10^{-11}m_{\rm N}c^2$. Nuclear energy as in a bomb or a reactor or a sun is in round numbers an MeV/nucleon or $10^{-3}m_{\rm N}c^2$. Gravitational energy under "practical" astrophysical conditions — if that's not an oxymoron — is $10^{-1}m_{\rm N}c^2$, 100 MeV/nucleon. So gravity power beats nuclear power which vastly overwhelms chemical power. That is

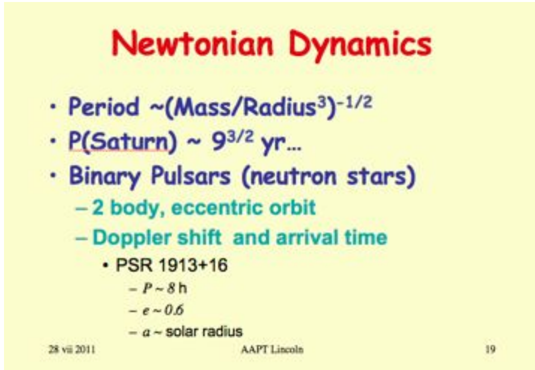

FIGURE 16

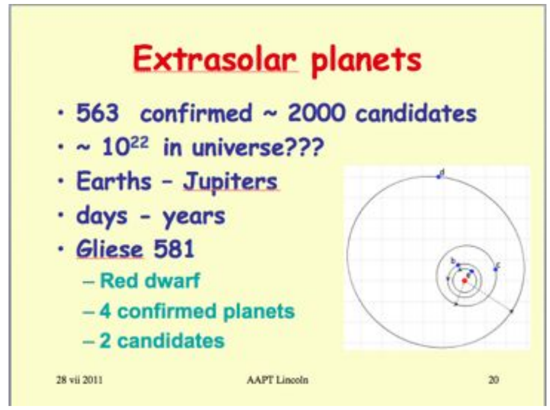

FIGURE 17

something the students don't always appreciate. They think that a nuclear weapon is like a big stick of dynamite. There is a BIG difference.

Energies: mc^2 for a star like the Sun is about 10^{54} ergs, but if you ask how much energy you get out consistently either as a result of nuclear reactions — either as a result of burning slowly over the lifetime of a star like the Sun or explosively like one of those supernovae that David showed you, it's 10^{51} ergs — 5×10^{-3} of its total rest mass. For an entire galaxy, I think you have to say that over its lifetime, including its nucleus producing radiant energy, it will produce about 10^{61} ergs. These are huge numbers.

I tried to organize this by physics topics rather than by astronomy topic, and then say how you might drag in a little bit of astronomy to help students appreciate the physics. It's not selling the astronomy; it's not marketing anything. It's where I think that you can enlarge the students' appreciation of the actual physics content of what we're talking about.

Newtonian dynamics of course describes the orbits around the Sun of the planets - what's left of them. Note in very round numbers that the radius of Saturn's orbit is 9 A.U. so the period is about 27 years, and so on. But you can do much more than that, especially now. I advertise particularly the binary pulsar. And the reason why I advertise it is that it is exquisitely accurate. Radio astronomers measure very, very carefully the arrival times of pulses from pulsars and with exquisite precision measure the orbits and indeed go on further than you need for these purposes to measure relativistic effects and so on.

But when you want to go from the planets going around the Sun to the two body orbits and the eccentric orbit rather than the circular orbit, then binary pulsars are great. Here's PSR 1913+16 [Hulse Taylor] Its period is 7.8 h; and its eccentricity is 0.6; the size of its orbit is about a solar radius. And it follows that orbit with exquisite precision.

There is another thing here that I think is conceptually interesting. Usually one thinks of using the Doppler shift — the Newtonian Doppler shift — as a way to measure the velocity of a moving body. But the way the radio astronomers actually do it is they measure the arrival times of pulses. That this is kinematically equivalent to measuring the Doppler shift is not obvious to the student. It's a good point to try and get across, and I think it develops basic understanding of these fundamental kinematics.

I've waxed lyrical about the extra-solar planets. As of this morning there are 563 that have got some Good Housekeeping certificate of approval. And there are about 2000 more candidates lurking out there, most of which are probably planets. It's a reasonable presumption that there are more than an Avogadro's number of them in the Universe, and, if anybody asks you, it is half possible that one of them exhibits more intelligence than we seem to be doing at the moment. So the range, the diversity is enormous — from Earths to Jupiters, days to years. Here is Gliese 581 which has been in and out of the news. I am not going to put my body between various astronomers who are or are not detecting planets, but I think it is fair to say that all of these planets are confirmed and some of the others may well be true. But still this is a pretty remarkable system. The star in the middle is not like the Sun; it's a red dwarf. Because its orbit has a short period, you get immediate gratification.You can make homework problems out of this. It's more fun than Jupiter or Saturn.

Thermodynamics. Here's another topic. Now the theory of stellar structure is one that has been developed from the nineteenth century through the twentieth century, along with the atomic and nuclear physics that it needed, up to the modern era of computation where you can compute with confidence the structure of main sequence stars, their evolution, and — there are certainly some parts of this that we do not understand and cannot describe while most of it is a glorious scientific success story including, especially,

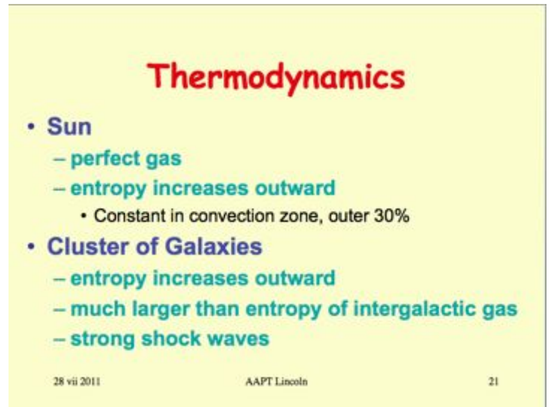

FIGURE 18

how the elements are made. A central part of this story is the thermodynamics — the thermodynamic properties of ionized and neutral gas; how its composition changes. And this in a simplified form is a splendid vehicle for bringing out the principles of equilibrium thermodynamics and statistical mechanics.

Entropy is always a big puzzle to students. You can get quite a lot of insight using stars. In the Sun, the entropy increases as you go outward from the core of the star to about 70% of the solar radius at which point it is constant because the outer parts of the Sun are convective. All the gas gets mixed up very fast and because it's an adiabatic process, entropy is effectively constant in that region. That connection I believe can be helpful in teaching regular thermodynamics.

Another example is clusters of galaxies that David showed you some examples of. The entropy of the gas around the galaxies that is measured by the x-ray astronomers increases outward like inside the Sun. A very recent discovery —"hot" off the press — is that the entropy in the outer parts of these nearby clusters of galaxies is remarkably high. We know from cosmology what the entropy is in most of these intergalactic media. We

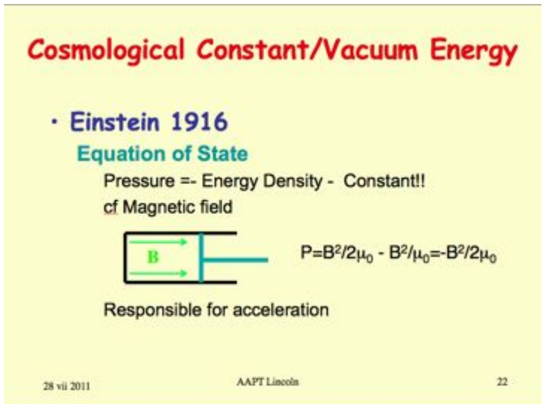

FIGURE 19

know what happened to it from recombination, when the microwave background formed, to reionization, when we see the first stars and galaxies. That entropy is very large, much larger in the outer parts of clusters of galaxies than it is in the intergalactic medium. How did that happen? Well, there really is only one answer. This is what David emphasized in a slightly different context in his talk. There has to be a very strong shock wave there. Shocks create entropy.

Let's do another type of thermodynamics in an esoteric form. It's something that's rightly very puzzling. I think that teachers probably avoid this in the first few years of physics instruction, but they are likely to be asked about it, because you read about it in the newspapers let alone in *Scientific American*. I am talking about dark energy. What is this stuff? It's most of the Universe and we don't know what it is. Well, Einstein invented it at some level in 1916; he called it the cosmological constant. And frankly in spite of all of the self important schemes of theoretical physicists to try and make it more rich and interesting, it looks like it IS a cosmological constant functionally. It is stuff that is just there; it is universal and eternal. Doesn't change; nothing happens to it; it's just there. You can call it the fabric of spacetime — I don't know what that means, but it sounds good. You can call it vacuum energy; that doesn't make much sense but that sounds even better. You can call it the aether, and that sounds awfully historical and getting into rather dangerous territory. However, be my guest. It is a sort of modern aether in some sense.

But if we take the view — and this is one of the possibilities you have — that it's a substance, its thermodynamics are very simply prescribed. You know physicists like to say its pressure is equal to minus its energy density; it's constant everywhere. Here is a good trick to try and elucidate this for a student who knows a little electromagnetism and knows that there's tension and energy density in magnetic field lines. The pressure of a magnetic field in one of these little imaginary cylinders here with the piston coming out is going to be the tension, which is going to be $-B^2/\mu_0$, plus the pressure which is $B^2/(2\mu_0)$ in SI units, which is just minus the energy density.

$$P = \frac{B^2}{2\mu_0} - \frac{B^2}{\mu_0} = -\frac{B^2}{2\mu_0} \qquad (1)$$

So just having a piston coming out in a uniform magnetic field is a very familiar thing and this seems almost trivial. But that is the equation of state in one dimension that because it's a scalar field we think it might be appropriate to dark energy if it's a cosmological constant. Certainly to within 10%, some would argue 5%, that is the measurement. And the odd thing here, of course — and I come back to it in a moment — this tension, this pulling together is paradoxically what is responsible for creating the acceleration of the Universe.

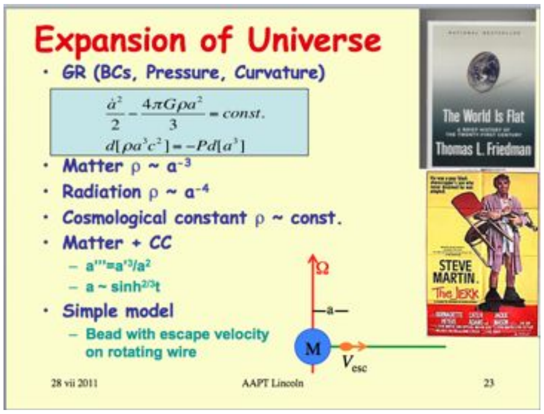

Figure 20

So let's go on to talk about the expansion of the Universe — this is a little bit more advanced, but it doesn't have to be a lot. And again you pick and choose this as appropriate to the level at which you're teaching. The cosmological expansion of the Universe is described by what are called the Friedmann equations. And this is basically what they are; and let's take the second one first.

This should look like thermodynamics. This second equation is the internal energy. I've got a box of stars and I get to say this box has a size a. And if I say how much energy density is there, it is ρc^2. So

$$d[\rho a^3 c^2] = -P\, d[a^3] \tag{2}$$

The left hand side of the equation is dU; the right hand side is $-P\,dV$. Equation 2 is just the first law of thermodynamics written down. Now it may happen to be the equation of state for dark energy, but that's all it is.

The other equation is this. This says that if I just imagine you and me — I'm here and you're a distance a away from me. Now let's write down a Newtonian energy equation:

$$\frac{\dot{a}^2}{2} - \frac{4\pi G\rho a^2}{3} = \text{const.} \tag{3}$$

and this, if you think about it, is a big sphere around me, and this is the gravitational potential energy with respect to me. Now you can say this is a Newtonian theory and say that's constant, and you go long enough, it'll be zero, etc. etc. Now this is a fraud. This thermodynamics equation, that's true. But this other is a fraud because it misses three key points that any student ought to be able to say "What about ...?"

First, the boundary conditions. Well, I said there's stuff around everywhere. What do I do at infinity?

The second is what about the pressure? We know the pressure can be big. We've just shown that. Does that contribute to the actual gravitational mass? Newton didn't know about it, but we should be worried about it.

And the third is curvature, especially about is the space flat or not?

And those are three big questions which general relativity brilliantly answers. So do not short change your students with a swindle. It's an easy way to remember the answer. And in fact the constant for flat space is zero.

You can do more with this. The energy density ρc^2 is just matter without any pressure — the stuff of you and me, the stuff of dark matter; it's all cold. No pressure. Or it's insignificant. It scales as $1/a^3$. If you are at early time, it's important to include the microwave background and the neutrinos that go along with them, and their energy density goes as $1/a^4$ because the energy of each photon in the microwave background is scaling inversely with the size of the box as it expands.

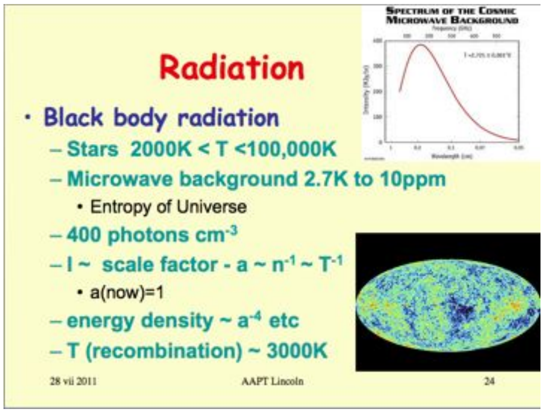

FIGURE 21

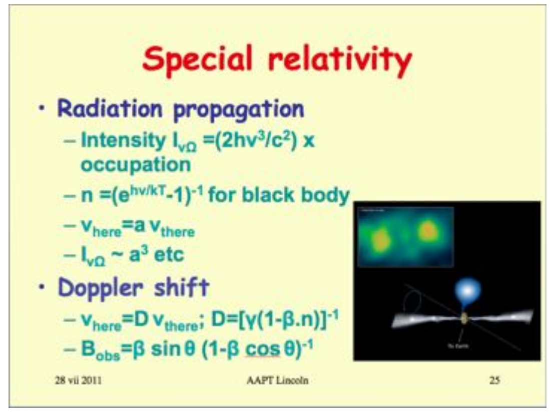

FIGURE 22

If we look at contemporary measurements, the matter of the cosmological constant is simple. Just combine these differential equations. The third derivative of the scale factor is the cube of the velocity divided by the square of the scale factor.

$$\dddot{a} = \frac{\dot{a}^3}{a^2} \tag{4}$$

So if it's independent of the scale factor, it didn't matter whether it was you or someone twice as far away as you. That's a very simple innocent third order differential equation. It's the jerk; (celebrated in this poster by one of the great physicists of contemporary life). I think it's kind of remarkable actually that that describes the Universe. In fact even more remarkable — and many students of cosmology don't actually appreciate it — it has an elementary solution

$$a \sim \sinh^{\frac{2}{3}} t. \tag{5}$$

which is the one that is appropriate; it just goes to the 2/3 power of the hyperbolic sine of the time scaled appropriately. That's all it is. So you can make a homework problem out of this that's pretty exciting.

Let's talk about radiation. This also comes up under thermodynamics. Again the microwave background is a spectacularly good black body. People talk about some metaphorical chip of coal or something like that as a black body. We've got stars, of course, that are good, but the microwave background is spectacular — 10 parts per million in the deviations, and these we actually understand. It is a perfect blackbody; it contains the entropy of the Universe — the photons, that's where most of the entropy lies.

The scale factor increases inversely with the frequency: The wavelength in the box it will fit in goes as the size of the box; the frequency will go inversely. The temperature is going to scale with the frequency. And you can get everything out of that as before. So at recombination when we see this microwave background at 3000 K, the Universe was a thousand times smaller than it is today; a million times the density; and so on.

We can use this in teaching special relativity. Here are the radiations. Consider how to deal with the radiation. Astronomers are doing this all the time. It's a trick — this is at a slightly higher level here — but it is

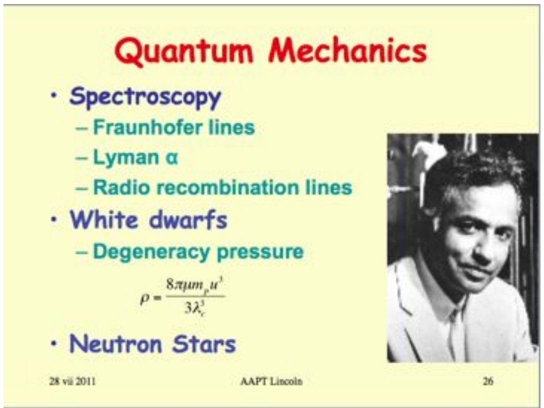

FIGURE 23

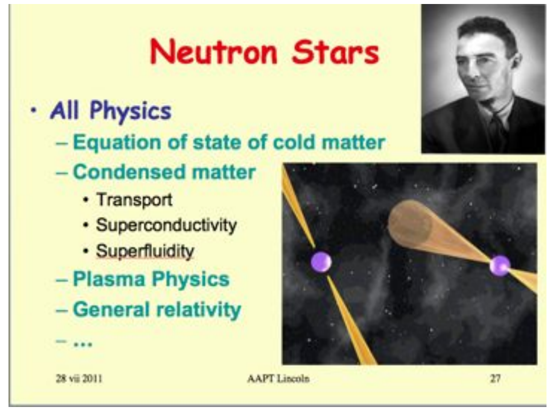

FIGURE 24

a trick that you can get an awful long way with. The key thing is to use the quantity that astronomers call intensity — per unit frequency, per unit solid angle. It's

$$I_{\nu\Omega} = \frac{2h\nu^3}{c^2} \times \text{ occupation number} \tag{6}$$

where the occupation number is

$$n = \frac{1}{e^{\frac{h\nu}{k_{\mathrm{B}}T}} - 1} \tag{7}$$

for a black body. $I_{\nu\Omega}$ goes as ν^3; therefore, it transforms as a^3 and so on. The frequencies transform that way.

Just focusing on the intensity and recognizing that n is a scalar is the royal road to describing how radiation gets from there to here. Additionally, it gives you the Lorentz transformation. Figure 22 gives the formula.

All of these results come just from this simple description of the intensity. And this is superluminal expansion which is nature's way of making special relativity necessary, so I won't make any more of that.

Quantum mechanics. I'm just going to go through this very quickly now. We can talk about it in a bit more detail later on if you want. Obviously spectroscopy is key: Fraunhofer lines; Lyman alpha is the central line from the Bohr theory of the hydrogen atom through the associated Laguerre polynomials from the Schrödinger equations and so on. Lyman alpha is the first line you come across and of course you don't see it in the lab because it's in the ultraviolet, but astronomers see it all the time. I'm sure Barbara will be mentioning this. White dwarfs provide another example of the uncertainty principle. Radio recombination lines illustrate the correspondence principle; you're going out to $n = 100$s in radio frequencies, and the allowed transitions from n to $n-1$ just have the angular frequency of an electron going around the Bohr orbit and so on. Again, astronomers measure these things. These are some of the examples you can use to illustrate the correspondence principle.

White dwarfs and the degeneracy pressure. This can be used to illustrate degeneracy, the Fermi surface, and the relevance of the Compton wavelength.

Neutron stars demonstrate essentially all physics with the possible exception of string theory. Figure 24 lists just some of the physics subfields.

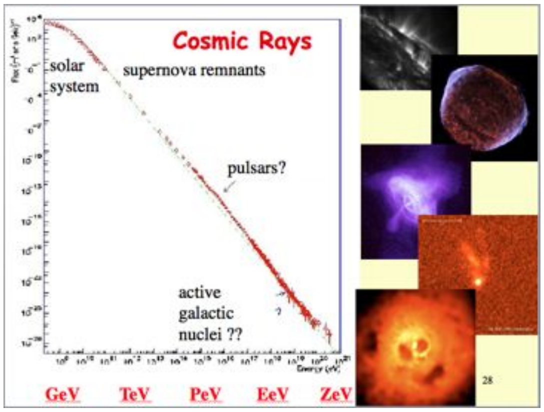

FIGURE 25. Images of possible sources of cosmic rays

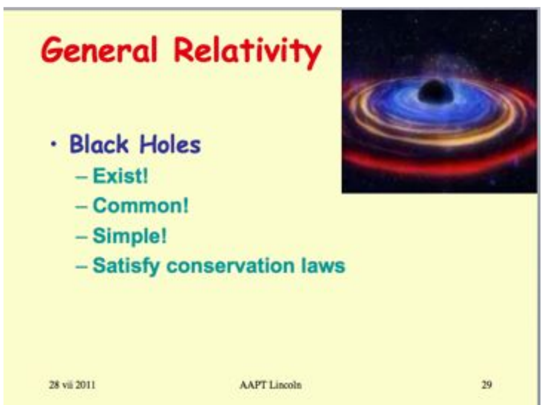

FIGURE 26

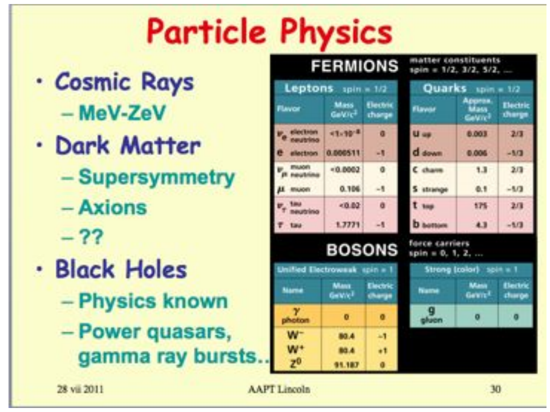

FIGURE 27

Particle physics and Dark Matter. Particle physics has its origins in cosmic ray physics. Here we go from GeV to TeV to ZeV. That is about 100 J out there, a well hit baseball — the energy; the momentum of a snail. That's an important distinction; particle physicists lose that sometimes, momentum and energy — they think they're the same, but regular physicists should know the difference. Figure 25 shows some sources of cosmic rays. There's a lot going on there.

General relativity: Finally, black holes. This picture is from a movie that I dislike. It's like a children's puzzle: How many things can you find wrong with this picture? It's shown all the time and it's wrong in so many ways I can't begin to start telling them. However, black holes exist; they are simple. They are like elementary particles: they are just characterized by masses that scale and something that measures the angular frequency of the scale. And that is it. They satisfy conservation laws: energy, mass, angular momentum — all the things that you know from regular Newtonian physics go over in discussing black holes. The physics is known in a curved spacetime. Any physics we can solve in a classical context, in a flat space, we can solve in principle in a curved black hole. And that's terribly important in astronomy because they power quasars and gamma ray bursts.

Let me finish. Something I was going to say a bit more about was numerical simulation. Astrophysicists have embraced this, particularly in cosmology. I'll show you one from black holes. This is a very recent calculation done by my colleague and collaborator Jonathan McKinney. There's the black (or

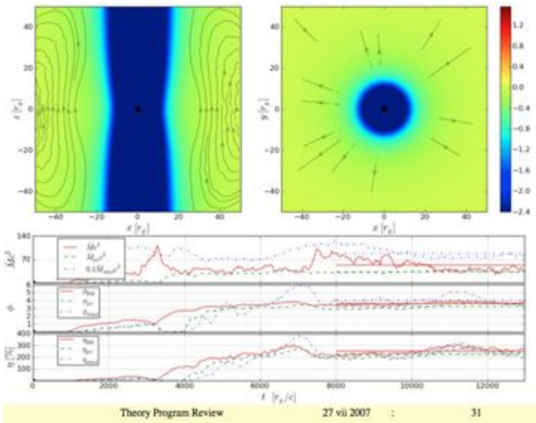

Figure 28

blue!) hole and these are the jets that David referred to somewhat pejoratively. They're coming out of the black hole. In this simulation, these are magnetic field lines; this is a possible explanation for how the jets that we showed you are being produced. But what is remarkable is that the simulation demonstrates something that had been conjectured for a while — that you could actually take spin energy of the black hole; reduce its mass; slow it down — just like you do with a pulsar — and it creates jets and winds. This is the jet, and these are the winds.

So let me finish at this point. I hope I've been able to convey a little bit of the field of possibilities that one can use to bring astronomy into standard physics education.

Thank you very much indeed.

C: Well, I said relating astronomy to physics instruction is a challenge, but it's a challenge you have met. That was terrific. Thank you so much.

I think there is time for two questions. And then we'll ask our other questions over coffee. Any questions? Or is everyone too eager for their coffee.

Well, I have just a comment. You mentioned that we're de-emphasizing analytical solutions. And you gave a reason that we should continue to . . . , but one reason that the analytic solutions are so important is that they provide a way to test your computations.

B: Absolutely.

C: I think some of the pitfalls in the growing reliance on computation are yet to be discovered.

B: I couldn't agree more with you. However, the elaborate Chandrasekhar style investigations using nineteenth century special functions that were brilliant intellectually, are now, I think, largely redundant. Simpler analyses are still very important because they not only develop intuition, they also provide checks of much more elaborate numerical simulations. I think we agree.

C: Yes, Joe?

Amato: This is kind of a philosophical question. You talked about the Friedmann equations, and they looked pretty much like Newtonian cosmology.

B: Yes.

Amato: Now the question I have is: When do you think it is allowable and profitable to cheat? You did use the word fraud.

B: Swindle is what I call it.

I think one should not cheat. I think you can say: This is the correct answer. You do not have the tools — in this case, differential geometry and general relativity, and so on — to understand the derivation of the Friedmann equations. That it looks like what you might get from Newtonian description is in fact pretty much a coincidence. There are cancellations. I can write those Friedmann equations in a different form where the other terms come in. And I just wrote them to look like Newtonian ones, and that's an easy way to remember them. As a mnemonic, I think it's great, but don't leave the students with a sense that they somehow derived the Friedmann equations properly.

Galvez: There's a similar analog to that and that is when you compute of a black hole and you come to the escape velocity . . .

B:. . . the escape velocity. A perfect example, yes . . .

C: Both of you finish your sentences.

B: Yes, go on. Sorry. You finish.

Galvez: That is another situation where you struggle, and it is so easy to do escape velocity equals c, and then apparently that's wrong.

B: Which is what Laplace and Michell did. And it is coincidence that Schwarzschild got the same answer; you don't get the same answer for a spinning hole.

C: Okay. I think it's time for a little escape velocity out to the coffee. We will resume at 11.