Type Ia Supernovae and Cosmology

White dwarf supernovae, aka Type Ia, are the focus of a sustained campaign of observations because they represent our best current probe of the relation between luminosity distance and redshift in cosmology. To see why, let's examine the evidence about this class and proposed mechanisms. Much of this is taken from Rosswog and Brüggen.

A key difference betwen Type Ia supernovae and the other classes is that whereas everything else only happens in galaxies with active star formation, Type Ia SNe can also happen in old elliptical galaxies where star formation has long since ceased. This tells us immediately that Type Ias can't be due to massive stars, because massive stars live a very short time. In addition, the specific kinetic energy of the matter ejected from a Type Ia is comparable to what one would get by fusing carbon or oxygen into iron. Explosive fusion requires degeneracy, which implicates white dwarfs.

To get a sense of what type of white dwarf is involved, note that low-mass white dwarfs ($M < 0.45\ M_\odot$) are typically made of helium, whereas more massive WD consist of carbon and oxygen. The latter are more reasonable to explain Type Ias (recall that the energy released in fusion declines sharply as the atomic number goes up). Very massive WD might be made of oxygen and neon.

In more detail, however, there is more than one model that might explain the phenomenology. The one that is currently in first place is that a white dwarf in a binary system accretes matter from a companion, and when the WD exceeds the Chandrasekhar limit, it starts collapsing. At this stage, the temperature and pressure go up rapidly in the center. This leads to fusion. The fusion then runs away; what we mean by this is that, unlike in the Sun and other stars where the fusion is stable, here the fusion occurs in a degenerate environment. The difference is that in a nondegenerate environment (e.g., the Sun's core), a slight increase in the rate of fusion leads to expansion and cooling, so the burning remains at roughly a constant rate. In the center of a white dwarf, however, the matter is degenerate. Therefore, an increase in temperature makes little difference to the pressure, so the burning keeps pushing the temperature upwards. End result: kablooey!

This model has the obvious advantage that since it happens at the same mass every time, it is reasonable to expect that (as is observed), the energy reservoir is pretty much constant. The difficulty, however, is in getting it to that state. Suppose that you have a white dwarf accreting matter. That matter is composed mainly of hydrogen and helium, therefore as it piles up it has the possibility of undergoing a burst of fusion itself. The problem is that in that fusion there is more energy available than exists in the gravitational binding energy of the matter to the surface. As a result, simulations show that in a cycle of accretion and a fusion burst white dwarfs typically *lose* mass! That makes it tough to grow to a Chandrasekhar mass. Some people suggest that if the accretion happens rapidly enough, the matter may fuse on the way, slowly, leading to mass gain.

The other main model is that helium piles up on a carbon-oxygen white dwarf, then ignites off-center. These don't need to accrete as much mass as the Chandrasekhar mass models, but there are difficulties in detail. For both classes of models there are severe problems in simulating the explosions. This is because the propagation of nuclear burning involves very thin and convoluted flame fronts with widths of less than a centimeter, as compared with the $\sim 10^8$ cm size of the white dwarf! Not an easy problem...

In both white dwarf supernovae and core collapse supernovae, one sees the glimmerings of hope that these sources could be used as standard candles. The reason is that for each source, a characteristic mass (the Chandrasekhar mass) is involved, so the the total energy release should not be overwhelmingly different from event to event. Note, though, that core collapse supernovae and white dwarf supernovae give significantly different photon luminosities (which is what is measured), so one can't lump all supernovae in one bin. Nonetheless, let's take a brief diversion into distance measures in cosmology, so that we can better appreciate the opportunity that is afforded to us by white dwarf supernovae.

Distance Measures

An excellent summary of various distance measures is given by David Hogg

(see http://www.arxiv.org/abs/astro-ph/9905116). He discusses:

- The *proper distance* D_P that we measure to an object is the distance we would get if we were to take a snapshot of the universe and directly measure (e.g., pace off) the distance between where we are and where the object is, at some fixed time.
- The *luminosity distance* D_L is how far an object of known luminosity L (measured in energy per time) would have to be in Euclidean space so that we measure a total flux F (measured in energy per area per time), that is, $D_L = \sqrt{L/(4\pi F)}$.
- The *angular diameter distance* D_A is the distance an object of known size l (say, one meter) would have to be in Euclidean space so that it appeared to be its measured angular size θ; that is, $D_A = l/\theta$.

Of course, even cosmologists have to encounter reality at some point. For example, when we measure the luminosity distance, we really want the *total* flux F, measured over all wavelengths, and the *total* luminosity L. However, as we go to higher redshifts, the wavelengths are themselves redshifted, so that for example the light we measure in the visible band might have started in the ultraviolet. **Ask class:** what are some complications that this might introduce in the measurements?

Answer: The problem is that we can only measure some of the radiation emitted by any given object. For example, hard ultraviolet radiation is tough to measure because it is easily absorbed by intervening dust and gas. If we use visible light to observe a galaxy at redshift $z = 4$, the light was very much in the ultraviolet when it was emitted (the wavelengths were a factor of $1 + z = 5$ shorter at the time). The result is that corrections must be made for this.

Back to Type Ias

In the 1990s, people focused in particular on white dwarf supernovae, because observations of them in galaxies with independent distance estimates suggested that their luminosities are clustered more than those of core collapse supernovae. There was still, however, enough variation from event to event (>20%) that they were not quite suitable for precision distinction between cosmological models.

Then, in 1993, a breakthrough occurred. In that year Mark Phillips published a paper showing that the peak luminosity of a white dwarf supernova is positively correlated with the time that it takes to decay from the maximum to some fraction of the maximum (or equivalently, how much it decays in the first 15 days after maximum). This is critical, because an independently measurable quantity gives a hint about the already pretty standard luminosity of these events. With this, or similar, corrections, white dwarf supernovae appear to be standard candles to better than 10%. This is good enough to do serious work.

The result is in Figure 1, which is taken from the Supernova Cosmology Project. The plot is essentially of luminosity distance on the vertical axis versus redshift on the horizontal, although the actual observable quantity is apparent magnitude instead of luminosity distance. That is, this is flux versus redshift. The curves show what is expected for different cosmological models. Here Ω_M is for matter, and Ω_Λ is for a cosmological constant.

The ultimate conclusion is that the universe is accelerating in its expansion, hence some bizarre "dark energy" is in play. We do have to be careful, though. First, from the plot we see that the scatter in the observations is dramatically larger than the differences between the curves. It is therefore necessary to rely on statistics: with many measurements, the centroid curve can be determined pretty well. More importantly, we have to worry about systematic effects. The fundamental observation is actually that white dwarf supernovae at a given redshift are slightly dimmer than expected if $\Omega = 1$ and there is no cosmological constant [compare the (1,0) curve with the (0.28,0.72) curve, and remember that higher magnitude means *lower* flux]. As Carl Sagan liked to say, extraordinary claims require extraordinary

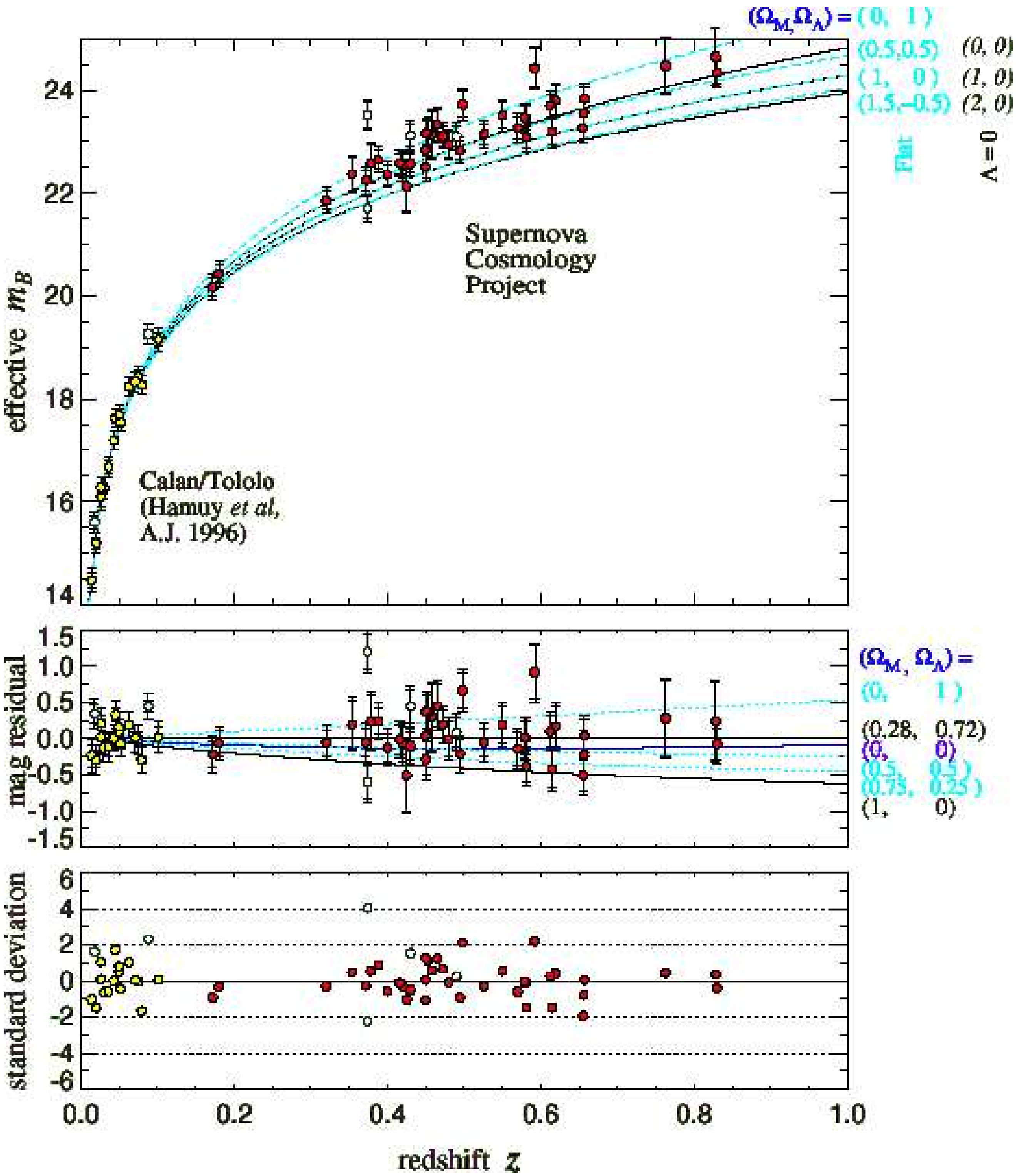

Fig. 1.— Magnitude vs. redshift of Type Ia supernovae. From the Supernova Cosmology Project.

proof. What other effects might cause slight dimming at large distances and/or earlier times, and can we rule them out?

Mundane Explanations?

One possibility is that light is getting absorbed or scattered along the way. This would work in the right direction, because more distant supernovae have to traverse a greater distance, and hence a larger amount of stuff, than nearer supernovae. **Ask class:** how would we test this?

The key is to realize that in the optical, where the observations are made, scattering is strongly wavelength dependent. The result is that if a lot of flux is lost to scattering, one also expects that the source should look redder than it does normally (for the same reason that sunsets are red; blue light is scattered out, but red light is not scattered as much). Therefore, an easy way to check for this effect is to see whether distant, dim supernovae look redder than close, bright white dwarf supernovae. The answer: no. In the spirit of checking all possibilities, we should note that if the "dust" is sufficiently large then the scattering is wavelength-independent for optical light. Such "grey dust", however, has not been seen, so it is rather ad hoc and not believed.

Another possibility is that white dwarf supernovae at redshifts of $z > 0.5$ genuinely were dimmer than they are now. This is something that must be taken seriously, for the simple reason that our theoretical understanding of white dwarf supernovae is relatively primitive (in contrast to, for example, Cepheid variables). **Ask class:** what might we do about this?

In general, we cannot test all hypotheses of this type, because maybe there is some unknown effect. What we can do, however, is make a specific guess at why supernovae at high redshifts are different from those now, and test that guess. One that seems physically reasonable is that the luminosity vs. decay rate relation somehow depends on the fraction of elements heavier than helium (aka the "metallicity"; astronomers are weird in that they call all elements heavier than helium "metals"!). For example, it could be that this affects the nuclear energy release or the accretion properties just enough to make a difference. One would then expect systematics with redshift, because the farther back in time we go, the less time the universe has had to synthesize metals in stars.

For this specific hypothesis, though, we can apply local tests. The reason is that even among local galaxies the metallicity varies all over the place, and in particular there are plenty of galaxies with metallicities as low as those at $z > 1$. Systematics would then be expected locally as well as with redshift, but they aren't seen. Whatever the details of white dwarf supernovae are, they appear robust against metallicity.

Another future test would be to look at white dwarf supernovae in a wider range of redshifts, say up to $z = 2$ or so. The point is that the flux versus redshift is predicted to have a specific form if it is cosmologically driven, but if there is some intrinsic effect it would almost certainly have a different form. Therefore, the better the statistics the greater our confidence.

Yet another possibility has to do with gravitational lensing. Light is deflected by mass, so the light from a white dwarf supernova takes some (minor!) turns as it wends its way to us. If we are in some favored location, then the flux we see can be amplified compared to what it would be with a smooth distribution of matter. However, lensing doesn't create light (it merely moves it around), so for every location with enhanced flux there are several with slightly diminished flux. At larger distances there are more chances to pass by lumps of matter, so this effect might be enhanced with increased redshift. **Ask class:** how might we test this out?

This is another effect that gets settled by statistics. Each new white dwarf supernova is an independent measurement, and we can therefore test whether the distribution of fluxes is as predicted from (1) a standard universe with gravitational lensing, or if it is better predicted by (2) a universe with accelerating expansion. As more observations have been made, it has become clear that (2) is the better option.

The net result is that although the supernova observers have been admirably open-minded to other effects, accelerating expansion has come through as the best interpretation. Cosmologists have therefore been forced to accept this bizarre effect as reality, and to try to explain it. In the next lecture we will also accept this, and talk about one form of dark energy: the cosmological constant.

Intuition Builder

In white dwarfs we argued that bursts of fusion would tend to kick off more matter than accreted in the first place. What is the situation for neutron stars?