A Brief History of Cosmology

People have been putting together cosmological histories for thousands of years. The majority of these, however, involve scenarios such as Earth being formed out of the eyebrow of a frost giant, and are not supported by the most modern data. We will therefore start our story with the first attempts at quantitative, predictive models of the universe, which began with the Greeks.

The Greeks were superb mathematicians and considered geometry to be the height of mathematics. They therefore interpreted observations in a way that involved mathematical aesthetics. For example, multiple lines of evidence pointed to a roughly spherical Earth (shadows on the Moon; different constellations becoming visible as one went south; apparent sinking of ships as they went towards the horizon in any direction). They generalized this to the idea that everything in the heavens is on spheres as well (at different radii). Since the "natural" motion of a sphere is to rotate, it followed that the universe consists of objects moving on rotating spheres.

Simple observation also demonstrates that the Earth is at the center of all these spheres. It is commonly asserted that the point was to place the Earth at the unique position of honor, but in fact the ancient Greeks and thinkers all the way up to Copernicus thought of it the other way around: the Earth was at the *lowest* place in the cosmos. Indeed, here things are obviously corrupt and changeable, whereas the heavens are pristine and eternal.

Another aspect of the universe considered clear by the ancients is that it is finite. For example, in his classic work "The Sand-Reckoner", Archimedes demonstrated that even with an absurdly large universe (based on Aristarchus' idea that the Earth moved around the Sun), one could estimate the finite number of sand grains that would fit inside. To have an infinite universe, one would require an enormous amount of wasted space, which is aesthetically unacceptable.

Looking back on this view of the universe, it may be tempting to dismiss it out of hand. After all, much of it was based on an imposition of a view of what the universe *should* do, and our experience since has shown us that the universe frequently doesn't care about our preconceptions!

However, a more objective assessment shows us that this is too simplified. The geocentric universe not only makes aesthetic sense, but it also conforms to common-sense observations such as our apparent stationarity, and we shouldn't forget that for a long time the geocentric model provided a remarkably accurate description of the apparent motion of planets.

In addition, as we will see, modern cosmology has its own set of simplifying assumptions and aesthetic preferences. The difference is that agreement with observations is considered to be the most important aspect of a model. In the last century or so, this has led us to extremely surprising conclusions about the cosmos. One of the most unsettling, yet productive, of those conclusions, is that we do not occupy a special place in the universe.

The Copernican Principle

The displacement of the Earth from the center of the universe was clear when it was established that we orbit the Sun. It has nonetheless been necessary to relearn that lesson several times. For example, could the Sun be the center? When we look at the night sky visually we see stars in all directions, with a cloudy band in one direction that is a little thicker at one point, but it is not at all clear what this means. Indeed, even as telescopes improved throughout the 1700s and 1800s, a number of people still believed that we were basically in the center. It took the observations of Harlow Shapley in the early 1900s to demonstrate that in fact we are offset from the center of the stars in our neighborhood. This was done using observations of globular clusters: collections of $10^4 - 10^6$ stars within a few parsecs that could even then be seen tens of thousands of parsecs away.

Like others before him, Shapley noted that obscuration by dust prevents a clear view of the stars around us, and hoped that the much more distantly visible globulars would do the job. He found that there is a significant excess of globulars towards the direction of Sagittarius, and concluded (correctly) that the center of their distribution was roughly the center of the stellar distribution. This in turn implied that the Sun was not at the center, although absolute distances were still difficult to establish.

From that point, of course, we have been displaced yet further. Our collection of stars is only one of billions of such collections, none of which have a special claim to be at the center. A still greater surprise is that we are not even made up of the dominant stuff of the universe: the protons, neutrons, and electrons that constitute essentially the entire solar system make up only about 4% of the universe. The remaining 96% is still not understood, and it is a fundamental goal of cosmology to resolve its properties.

The lesson, therefore, is that as a first approximation we can say that we do not live in a special place or time in the history of the universe. There are, however, some interesting coincidences that we will encounter in this course that suggest to some that there are exceptions to this principle.

Olbers' paradox

To address whether the universe is infinite, we can appeal to an argument called Olbers' paradox, which is so named because (as my advisor Sterl Phinney liked to say) Olbers was the fourth person to state the paradox and the second to give the wrong answer!

The question can be phrased simply: why is the sky dark at night? Basically, if the universe were infinite, then every line of sight would eventually hit a star, and thus the entire sky would have the same surface brightness (meaning energy per time per area per solid angle) as the Sun. We'd notice that! In the remainder of this lecture we will explore this paradox quantitatively.

First we'll start with the fundamental idea.

Ask class: Suppose that the universe is populated randomly with stars, but that the number density of stars is n (this is the number per unit volume). Looking out from Earth, consider a spherical shell between distances r and $r + dr$ from us, with $dr \ll r$. How many stars do you expect in that volume?

Answer: The volume of the spherical shell is $4\pi r^2 dr$, so the expected number of stars is $dN = n4\pi r^2 dr$.

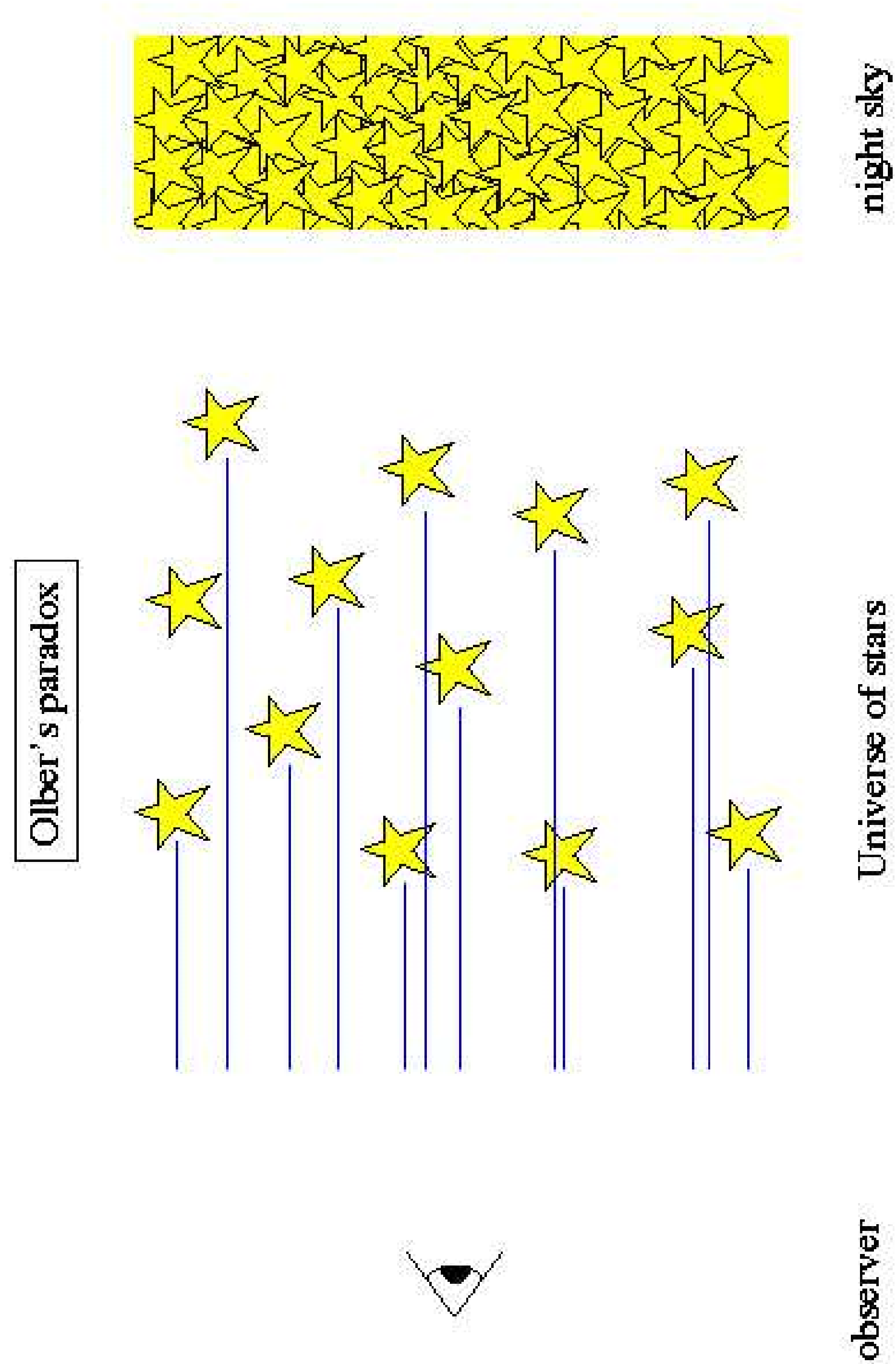

Fig. 1.— Olbers' Paradox. Every line of sight eventually intersects a star, so why is the sky dark at night? Figure from http://abyss.uoregon.edu/∼js/images/olbers_paradox.gif

Ask class: Suppose that each star has the same luminosity (energy per time) L, and that they emit equally in all directions. At a distance r from us, what is the flux (energy per area per time) that we observe from a *single* star?

Answer: The area at a distance r over which the light is spread is $4\pi r^2$, so the flux is $F = L/(4\pi r^2)$.

Ask class: Combining your results from (a) and (b), integrate the total flux we should see from stars at distances $r = 0$ to $r = \infty$. This is Olbers' paradox.

Answer: We want to integrate the flux per star times the number of stars per spherical shell, over all spherical shells. From distance r_1 to r_2 this gives a total flux

$$F_{\rm tot} = \int_{r_1}^{r_2} F\,dN = \int_{r_1}^{r_2} [L/(4\pi r^2)] n 4\pi r^2\,dr = \int_{r_1}^{r_2} nLdr = nL(r_2 - r_1)\ . \qquad (1)$$

As $r_2 \to \infty$, this clearly becomes as large as one would like, hence one expects infinite flux in an infinite and eternal universe.

At this point we have a problem, in that there is a conflict with observations. One way out, of course, is that the universe is not infinite, not eternal, or both. If we could conclude this, it would represent a fantastically important inference about the cosmos. We are therefore obliged to think about other possible ways out, and how to test them, before we can draw any confident conclusions. **Ask class:** what are some *other* possible ways out for us to explore? Examples include absorption by dust and a non-uniform universe.

Ask class: As our first try at resolving the paradox, we will consider the suggestion of Olbers himself. He suggested that since there exists gas and dust between the stars, the gas and dust would absorb and block the radiation. Evaluate this suggestion in the case that the observable universe is not only infinite, but eternal.

Answer: Olbers' suggestion doesn't work. This is because the gas and dust would heat up to the temperature of the illuminating stars after a finite time, so they would radiate just as much. You can't sweep this problem under an absorbing rug!

Ask class: Now suppose that the universe is infinite and eternal, but is *not* uniform. Specifically, let us say that the number density of stars is proportional to r^{-p}, where r is the distance from us. What are the restrictions on p so that the total flux we observe is not infinite? Some fractal universes are like this. What observations can you bring to bear to determine if this is a valid solution to the paradox?

Answer: If $n = Cr^{-p}$, where C is some constant, then from (c) the total flux becomes $F_{\rm tot} = \int nLCr^{-p}dr = nL(r_2^{1-p} - r_1^{1-p})/(1-p)$. For this to remain finite as $r_2 \to \infty$ requires $p > 1$. We can test this by seeing if the voids in the distribution of galaxies continue to increase in size as we look farther out in the universe. They don't; instead they tend towards a uniform density, so a fractal universe is ruled out.

Ask class: How far do we actually have to go for the paradox to become a problem? The average number density of stars in the vicinity of the Sun is about one per cubic parsec. Assuming that all stars have the same luminosity as the Sun, and noting that the Sun is 1/200,000 parsecs from us, how far would you have to go for the total luminosity of other stars to equal that of the Sun? The average number density of stars in the universe is actually another factor of 10^9 less than that, so how far would you have to go in that case? For comparison, roughly how large is the observable universe?

Answer: If $L_\odot$ is the luminosity of the Sun, the flux we get from it is $F_\odot = L_\odot/(4\pi r_\odot^2)$, where $r_\odot = (1/2 \times 10^5)$ pc. At a distance R from us, part (c) indicates that the combined flux of all other stars is $F_{\rm tot} = nL_\odot R$, where we assume the lower limit to the integration is much less than R. Therefore, $F_\odot = 3 \times 10^9\, L_\odot$ pc^{-2}, and thus we need to integrate to a distance $R = 3 \times 10^9$ pc$^{-2}/n$ to equal this flux. If $n = 1$ pc^{-3} this means a distance of 3×10^9 pc; which is just slightly less than the radius of the observable universe but much larger than the radius of our Milky Way galaxy. If $n = 10^{-9}$ pc^{-3} you'd have to go out to 3×10^{18} pc, a lot larger than the universe! The main resolution of Olbers' paradox is that the observable universe is finite (redshifts make a secondary contribution); a pretty profound conclusion to draw from dark night skies!

Intuition Builder

Olbers didn't know about black holes, but do they provide an alternate solution to his paradox? That is, they can absorb light the same way dust does, but unlike dust they don't heat up (in fact, they effectively become colder). It appears that all large galaxies have supermassive black holes at their centers and probably hundreds of millions of stellar-mass black holes distributed throughout. Could we therefore argue that if we go far enough the black hole "optical depth" is enough to absorb light that is too distant, therefore allowing an infinite and eternal universe?