SNAP and multiply-imaged supernovae

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ABSTRACT

SNAP can be expected to see handfuls of multiply-imaged supernovae per year. Each system would appear as multiple supernovae, closely spaced on the sky, with time delays of weeks to months between the different images. Since having a standard candle is inessential to most lensing studies, SNAP's large sample of type II SNe makes an important contribution to this strong lensing rate. Each case of strong lensing allows for a precise determination of time delays, image separations, and relative image magnifications, and the SNAP strong lensing database will offer measures of Ω_m, Ω_Λ, and H_0, *independent* of SNAP's primary goal of establishing the distance-redshift relation. These systems also constrain models for the matter density profiles of galaxies and clusters. Furthermore, lensed type Ia supernovae afford the opportunity to break the mass-sheet degeneracy found in many lensing measurements. The SNAP mission will provide, as a matter of course, one of the most thorough databases of uniformly selected strong lensing events ever produced.

1. Introduction

Multiple imaging due to gravitational lensing is one of the most spectacular consequences of general relativity. First predicted in 1937, it was the discovery of the first multiply-imaged quasar in 1979 which firmly established the field of gravitational lensing as an observational science. Multiply-imaged systems offer a number of important astrophysical probes. The likelihood of multiple imaging is related to the cosmological parameters Ω_m and Ω_Λ. The time delays between images can be used to estimate the Hubble constant. In addition, the distribution of image separations and image morphologies can be used to constrain the dark matter.

One of the most dramatic examples of strong lensing would be the multiple imaging of a supernova. A multiply-imaged SN would appear as multiple SNe, closely clustered on the sky ($\lesssim 15''$), with time delays between the "different" SN ranging from weeks to months. Each image would appear identical (same redshift, same colors, same light curve), modulo an overall shift in amplitude.

Because the strong lensing rate, even at high redshift, is still quite small ($\lesssim 0.1\%$ at $z = 1.5$), and because the incidence of SNe is roughly one per galaxy every 50 years, many millions of galaxies need to be observed to ensure reasonably good statistics. In addition, because of the time delay between images, these galaxies need to be repeatedly observed over the course of weeks and months to ensure identification of multiple images. Given the resources required, it is not surprising that a multiply-imaged SN has not, to date, been observed.

In the following we discuss the likelihood of strong lensing of supernovae, paying particular attention to the SNAP mission. We then discuss some of the science that can be accomplished by multiply-imaged SN. We follow closely the discussion of Holz (2001); see also Porciani & Madau (2000) and Bergström et al. (2000).

2. Likelihood

As one probes to higher and higher redshift, the probability of strong gravitational lensing increases dramatically. For example, for an $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ universe, the probability of having a strong lensing event for a given point source at $z = 0.5$ is 10^{-4}, rising to 10^{-3} by $z = 1.5$. This means that surveys would have to see on the order of thousands of SNe at such high redshifts to be expected to see significant numbers of multiply-imaged events. At present ~ 100 high-z SNe have been observed, and unless we were extraordinarily lucky, we would not expect any of these SNe to be multiply imaged. Even if one of the observed high-z SNe happens to be multiply-imaged, it is exceedingly unlikely that we would stumble upon successive images. Thus current state-of-the-art surveys cannot be expected to find multiply-imaged SNe.

SNAP, however, is almost ideally suited to find multiply-imaged SNe. SNAP's primary goal is to provide a detailed measurement of the distance-redshift relation. To do this, SNAP will use type Ia SNe as standard candles. This requires very detailed light curves of thousands of high-z SNe, which SNAP will achieve through repeated deep images of a number of large fields over a period of many months. This is precisely the strategy one would want to employ to find multiply-imaged SNe.

A detailed study of strong lensing in the SNAP observing program can be found in Holz (2001). SNAP's "optical" (0.3–1.0 μm) imager would observe 3,800 type Ia SNe per year, with detailed follow-up (restframe B-band photometry and spectra) of a subsample of 2,400 (100 at $z > 1.2$, and all at $z \leq 1.2$). Convolving the probability for a strong lensing event with the expected redshift distribution of SNAP SNe (relatively flat, with $1,500$ type Ia's/year at $1.2 < z < 1.7$) yields an expectation of 2 multiply imaged Ia SNe per year.

A great advantage of the SNAP program is its care in homogeneously selecting SNe. It will provide a 28.5 (restframe U or B-band) magnitude-limited sample of all SNe which occur during its observation period in its 20 fixed $1\,\square^\circ$ fields of view, with two fields being additionally imaged down to a limiting magnitude of 30. Since the gap between deep images of each field will always be less than eight days, no SNe will fall through the observing cracks (especially when time dilation of the light curves of high-z SNe is taken into account). Although the SNAP design is still in flux, we take as one of its core requirements that all type Ia SNe with $z < 1.7$ will be discovered at least 3.8 magnitudes below peak brightness (and thus within ~ 2 rest frame days of the explosion). Therefore lensed images which have $> 3\%$ of the (unlensed) source flux will be observed. From Holz (2001), we find that 94% of strongly-lensed events are at least this bright. SNAP will see *every* type Ia SN out to redshift 1.7 in its deep fields, and will observe the vast majority of strong lensing events of these sources, thereby minimizing magnification bias in the strong lensing sample.

SNAP will also see a very large sample of type II SNe (though only a tiny fraction will be followed up). While these are significantly dimmer (peak value 2.3 magnitudes below the Ia peak (in restframe B-band), with a dispersion of 1.3 mag), they also occur at much higher rates (3 times more frequent at present day, rising to 5–10 times more frequent at redshift 1–2). Taking a conservative value of 5 times the Ia rate, we find that SNAP would have 10 multiply-imaged type II SNe in its sample per year. SNAP will catch the average type II event only 1.5 magnitudes below peak, and so will miss images demagnified to less than 25% of the unlensed flux. Convolving the large intrinsic dispersion in type II peak brightness with the distribution of image pair magnifications (Holz & Wald 1998), we find that 60% of multiply-imaged type IIs will be observable, yielding an expected total of 6 events per year. For these systems, SNAP's optical imager light curve will provide a precise determination of the image time delays, separations, and relative fluxes. As one does not require the standard candle luminosities of lensed SNe to do strong lensing science (see below), strongly lensed type II systems are a valuable contribution to the lens database.

In this discussion we have restricted our attention to the SN sample at $z \leq 1.7$. SNAP will also image SNe at higher redshifts, though without detailed photometry/spectrometry. Lensing magnification will further extend the sample, allowing SNAP to probe a much larger volume of space, and to higher strong lensing optical depth. This additional magnitude-limited sample could very well include additional multiple-imaging events.

Combining the rate for SNe Ia and II, we estimate that SNAP will detect 8 multiply-imaged SNe per year. Temporarily relaxing our conservative assumptions (e.g. taking more generous optical depth and SN II rates, allowing for magnification bias), we find that 30 multiply-imaged SNe per year would not be unreasonable.

It is to be noted that SN multiple imaging events with image separations much less than the resolution of a given telescope can still be identified and explored. This is because, as long as the light curves of the different images do not significantly overlap in time, proximity (and blending) of the images is no impediment to observation. In addition, it is straightforward to associate even very widely spaced images, as we expect to see all SNe within SNAP's large ($1\,\square^\circ$) field of view (limited to systems with time delays which fall within the SNAP observational period).

3. Science

The probability of having a strong lensing event, at a given redshift, is a sensitive function of the cosmological parameters. For example, larger values of the cosmological constant increase the volume of space to a given redshift, and therefore increase the lensing rate. By measuring the lensing rate, one can thus infer values of Ω_m and Ω_Λ. In addition, the lensing is quite sensitive to the form (e.g. microscopic or macroscopic, non-interacting or self interacting) and clumping (e.g. isothermal or NFW) of the dark matter. Thus measures of the lensing rate, and the distribution of image separations and time delays, can be used to constrain fundamental properties of the dark matter (Metcalf & Silk 1999; Seljak & Holz 1999). In practice, however, such measurements have been plagued by selection effects, which sharply reduce their utility as cosmological probes. Given the limitations of current instruments, only a few uniformly selected deep lensing surveys have been attempted. The most notable of these is the JVAS/CLASS survey, which has identified over 15 multiply-imaged flat-spectrum radio sources, out of a sample of over 15,000 (Myers et al. 2001). After a few years observation, SNAP's sample of SNe will rival this database, both in number of objects, and quality of observations. Each of the SNe in the SNAP database will have a full, multi-color light curve, with a subset having in addition a detailed spectra at at least one epoch.

Multiply-imaged systems also allow for the determination of the Hubble constant, H_0, through the measurement of time delays between images. Identifying the time delay in a multiply-imaged system generally requires both a time-varying source, and coordinated observations of the images over a course of weeks or months. A number of lensing systems have had devoted monitoring regimes to determine time delays and mass models, with a handful of systems now having reliable time delay measurements (Kundić et al. 1997). In the case of multiply-imaged SNe observed by SNAP, the determination of time delays will be entirely straightforward. SNAP will have repeated observations of every SN in its sample, allowing a direct determination of the time of peak luminosity of each image. In addition, due to the extensive phenomenology of SN light curves, the flux ratios (and in some cases absolute fluxes) of all images will also be well determined.

Unfortunately, none of the strong lensing systems with established time delays have mass models simple enough to allow for a "gold-plated" Hubble constant measurement. A major impediment to constraining lens profiles is the limited number of constraints a lens system provides (at best, a handful of image separations, relative brightnesses, and time delays). Attempts to increase the number of constraints generally rely on utilizing lensed images of the extended background galaxy (arcs, Einstein rings, etc.). For quasars these attempts can be hindered by the large brightness contrast between the quasar source and the rest of the host galaxy. In the case of SNe, however, the images conveniently turn themselves off, allowing an uncontaminated view of the host. To establish a baseline for the light "contamination" to the SN curve from the host galaxies, SNAP will make deep images of the hosts both before the SNe appear and after they fade away. Subsequent very deep observations with a variety of different instruments (e.g. NGST, CELT+AO) at a range of wavelengths could also be made. These images of the *lensed* host galaxy would provide important additional constraints to the lens model.

It is to be emphasized that much of the science that could be done with SNAP's sample of multiply-imaged SNe does not utilize the standard-candle nature of the SNe. Measurements of cosmological parameters, such as Ω_m and Ω_Λ, require only the statistics of strong lensing events.

Since these are independent of the intrinsic luminosity of the sources, they are complementary to the primary mission of SNAP (using the standard-candleness of type Ia SN to measure the distance-redshift relation). Thus SNAP will, as a matter of course, be able to make two essentially independent measures of cosmology. The measurement of time delays is also completely independent of the brightness of the SNe, and therefore the determination of H_0 from strong lensing does not depend on the traditional, Cepheid-based distance ladder.

Because type Ia supernovae appear to be very good standard candles, however, they also offer the unprecedented ability to measure absolute magnifications of lensed images. This would directly break the mass-sheet degeneracy commonly found in lensing measurements: a uniform sheet of matter anywhere between the source and observer will generally remain undetected. Because type Ia (and to a lesser degree type II) SNe are standard candles, the *absolute* magnification can be determined, yielding an additional constraint (by changing the relative fluxes of all images into absolute fluxes), and breaking this degeneracy.

An additional feature of SNAP is that, in the course of returning to the same fields week after week looking for new SNe, it will make very high quality weak lensing maps. Coupling information from both weak and strong lensing studies of a given field may yield additional insights—for example, a mass concentration which causes a large-separation multiple-imaging event may also be detectable in the weak lensing map of the same field. Any SNe (strongly lensed or not) superposed on a weak lensing map will (in principle) allow for a breaking of the mass sheet degeneracy.

4. Conclusions

The observation of multiply-imaged SNe would provide a scientific windfall. Not only would such systems afford independent measurements of the cosmological parameters, they would also constrain the matter distribution of galaxies and clusters, and yield insight into the composition of the dark matter. Although current high-z SN surveys are unlikely to observe a multiply-imaged SN system, SNAP would be expected to see at least 8 such events per year. Over a few years, SNAP will provide an extensive database of uniformly selected strong lensing events. These systems would be a boon to science, independent of and in addition to the primary goal of SNAP.

REFERENCES

Bergström, L., Goliath, M., Goobar, A., & Mörtsell, E. 2000, A&A, 358, 13

Holz, D. E. 2001, ApJ, 556, L71

Holz, D. E., & Wald, R. M. 1998, Phys. Rev. D, 58, 063501

Kundić et al. 1997, ApJ, 482, 75

Metcalf, R. B., & Silk, J. 1999, ApJ, 519, L1

Myers, S.T. et al. 2001, in preparation; see the CLASS homepage http://info.aoc.nrao.edu/~smyers/class.html

Porciani, C., & Madau, P. 2000, ApJ, 532, 679

Seljak, U., & Holz, D. E. 1999, A&A, 351, L10

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