Peculiar Velocities from Type Ia Supernovae

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Abstract.

Type Ia supernovae have only recently been employed to measure the peculiar motions of galaxies. The great distances to which SNe Ia can be seen makes them particularly well-suited to constraining large-scale velocity flows. The high precision of SN Ia distance measurements limits the contamination of such measurements by Malmquist or sample selection biases. I review the recent use of SNe Ia to measure the motion of the Local Group (updated to include 44 SNe Ia). The direction of the best-fit motion remains consistent with that inferred from the CMB (though modest bulk flows cannot be ruled out) and inconsistent with the Lauer-Postman frame. Comparisons between SN Ia peculiar velocities and gravity maps from IRAS and ORS galaxies yields constraints on the mass density which gives rise to the gravitationally induced peculiar motions. Indications are for $\beta=0.4$ from IRAS, and 0.3 from the ORS, with $\beta > 0.7$ and $\beta < 0.15$ ruled out at 95% confidence levels from the IRAS comparison. The contributions of SNe Ia to peculiar velocity studies are limited by statistics, but the great increase in the recent discovery rate suggests SNe Ia may become increasingly important in constraining flows.

1. What’s been done

Type Ia supernova (SNe Ia) are a newcomer to the toolbox used for measuring peculiar velocities and flows. Yet, with the rapid increase in the sample size and precision of distance estimates to these luminous disruptions of white dwarf stars, SNe Ia show great promise in this field.

I will begin with a review of the published literature (of only 4 or 5 articles) of the applications of SNe Ia to flow measurements.

The first attempted use of SNe Ia for flow measurements began in the “low-precision era” which lasted until the early 1990s. This era was characterized by the use of photographic photometry and the assumption that SNe Ia were perfect “standard candles” with homogeneous luminosity and colors. Such data and philosophy yielded distance estimates with approximately 25% uncertainty. Additionally, the sample of SNe Ia were concentrated at much closer distances than the present (and future) sample.

Using 28 primarily photographically observed SNe Ia, Miller & Branch (1992) were able to discern the gravitational influence of the Virgo cluster, i.e. Virgocentric infall. Because the average depth of their sample was only about
$cz=2000\ \text{km s}^{-1}$, their analysis was insensitive to the motion of the Local Group and the influence of the Great Attractor.

Jerjen & Tammann (1993) analysed a similar sample of 14 SNe Ia with an average depth of $cz=3000\ \text{km s}^{-1}$ (again under the assumption of homogeneity of luminosity) but could not detect the motion of the Local Group.

By 1996, work by Phillips (1993), the Calán/Tololo Search (Hamuy et al. 1996a,b,c,d; Maza et al. 1995) the CfA Group (Riess, Press, & Kirshner 1995a, 1996) and others (see Branch 1998 for a review) demonstrated that with high-quality CCD light curves and application of relations between the peak luminosity, light curve shapes and color curve shapes, individual distance estimates to SNe Ia could reach observed precisions of 5-7%. These improvements and the growing sample of CCD light curves ushered in the “high precision era”.

An analysis in my thesis (Riess, Press, & Kirshner 1995b) of 13 new SNe Ia from the Calan/Tololo Search made the first detection of the motion of the Local Group using SNe Ia. The sample had an effective depth of $cz=7000\ \text{km s}^{-1}$ and a typical distance precision of 6%. At this time, no corrections were applied for host galaxy extinction, though the members of the sample exhibited little reddening. Interestingly, the SN Ia measurement was strongly inconsistent with the large bulk flow observed from brightest cluster galaxies by Lauer & Postman (1994), a significant result since it was the only other sample at a similar depth. Nearly all of the observed disagreement occurred in the Galactic $\hat{z}$ direction. Despite the likely effects of correlations of small-scale flows (Feldman & Watkins 1995), the measurements remained in conflict. However, the relative imprecision of the SN Ia measurement could not rule out more moderate bulk flows on these scales.

Recently I have updated this measurement using the light and color curves of 44 SNe Ia with effective $cz=5000\ \text{km s}^{-1}$. This sample has been corrected for host galaxy extinction using the multicolor light curve shape method (Riess, Press, & Kirshner 1996). The results, show in Figure 1, are highly consistent with the previous SN Ia measurement, but have greater precision. The best-fit dipole is consistent with the CMB dipole. Relocating the SNe Ia into the CMB frame results in no measurable bulk flow (the debiased flow is negligible) with a 1$\sigma$ uncertainty of 150 km s$^{-1}$.

An analysis by Riess, Davis, Baker, & Kirshner (1997) compared the observed peculiar motions of 25 SNe Ia with $cz < 10,000\ \text{km s}^{-1}$ to those predicted from the IRAS and ORS gravity maps (Nusser & Davis 1994). The predicted peculiar velocities of SNe Ia are a function of the local mass in the Universe ($\Omega_M$) as well as the degree to which the positions of galaxies indicate the location of mass (i.e., the bias parameter). Together these unknowns are quantified by the density parameter, $\beta = \Omega_M^0/\lambda$. The comparison of the observed and predicted peculiar velocities of SNe Ia yields a statistically adequate match as well as strong constraints on the value of $\beta$. The fact that the observed and predicted peculiar velocity estimates concur (for the best-fit $\beta$) supports the gravitational instability paradigm as the source of peculiar flows. The results of the analysis are $\beta = 0.40\pm0.15$ from the IRAS comparison (and $\beta = 0.30\pm0.15$ from the ORS comparison, reflecting the relative biasing of infrared and optically selected galaxies). Bootstrap resamplings of the gravity maps and the SN Ia sample confirms the validity of the uncertainties.
Although mentioned previously by others in this conference, for completeness we mention an analysis by Zehavi, Riess, Kirshner, & Dekel (1998) which gives a marginal indication of a so-called “Hubble Bubble”. From 44 SNe Ia, Zehavi et al. (1998) found an indication at the 2-3σ confidence level of a local excess expansion of 6% within 7000 km s\(^{-1}\). This increase in the global Hubble expansion appears to be compensated by a small decrease beyond this depth after which the Hubble expansion appears to settle to its global value. The model proposed by the authors is that we may live within a local void bounded by a wall or density contrast at \(~\sim\)100 Mpc. More SNe Ia (and other distance indicators) will be required to test this provocative result.

2. The Future

Type Ia supernovae are an attractive tool for contributing to the measurement of peculiar velocities and flows in the future. SNe Ia provide independent means to measure flows at depths unreachable by many other distance indicators. The individual distance precision of SNe Ia results in a reduction of systematic errors like Malmquist and sample selection biases which often plague peculiar velocity studies. Individual SNe Ia can be corrected for line-of-sight extinction, eliminating a reliance on Milky Way extinction maps or inclination corrections. Finally, the pace at which SNe Ia are discovered is growing. By 1999 July 5 SN 1999da had already been discovered, starting the 5th cycle through the alphabet after only half a year! In 1998, 20 new SNe Ia with \(cz < 0.1\) were added to the sample which is useful for peculiar velocity studies.

A new era of nearby supernova searches is underway. Below we list in “bullet-form” searches and collection programs including some of their members, facilities, start dates, and successes.

- Mount Stromlo & Siding Springs Observatory SN Search (Schmidt, Germany, Stubbs, Reiss)
  Up since 1996, 2.3 m at MSSSO, > 20 SNe Ia at \(z < 0.1\) so far...
- Beijing Astronomical Observatory SN Search (Li, Qiu, Hu, etc.)
  Up since 1996, 0.6 m at BAO, 13 SNe Ia at \(z < 0.1\) found so far...
- Lick SN Search (Filippenko, Li, Treffers, etc.)
  Up since 1997, KAIT robotic telescope, 16 SNe Ia at \(z < 0.1\) found so far...
- Supernova Cosmology Project Nearby Search (Perlmutter, Aldering, etc.). Started in 1999, many telescopes, \(~\sim\)7 SNe Ia at \(z < 0.1\) found so far...
- CfA Program (Kirshner, Jha, Garnavich, Schmidt, Riess, etc.)
  Collecting since 1993, \(~\sim\)50 SNe Ia collected so far...
- Others: Perth, EROS, Wise, Tenagra, J. Maza, T. Puckett, W. Johnson, etc

What have the past and present searches produced so far? I have compiled the list of all SNe Ia to date which met the following requirements:
- CCD photometry
- \(z < 0.1\)
- enough observations recorded to yield precise distances

This list has 115 SNe Ia. Their positions on the sky and depth can be see in Figure 2. About half of these data have been published already (29 from Hamuy...
et al. 1996; 29 from Riess et al. 1998, 1999; 15 others in the literature) and the rest are “in the cans” of the various searches listed above. The average depth of this sample is 11,000 km s\(^{-1}\) and the effective depth for flow measurements is 5,000 km s\(^{-1}\). There are 60 objects with \(cz < 10,000\) km s\(^{-1}\). By looking at Figure 2 we note a few points. Although the distribution between Galactic North and South is not heavily skewed, there are more objects in the North. The typical depth in the South is somewhat greater. The zone of avoidance has been strongly avoided to date. Some concentrations like the Perseus-Pisces Supercluster and Coma are not probed while others (Virgo and Fornax) are well probed.

Although there has been little coordination in the past between searches, the results are impressive. This sample, and the ever growing future sample, will be a powerful data set with which to measure the peculiar motions of test particles subject to gravity in the Universe.

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