The velocity field and 3-D structure of the Universe

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Abstract

The velocity field of matter in the Universe is dominated by the Hubble expansion, and the 3-D structure is characterized by sheets with high density of visible matter separated by large voids. A superposed large-scale streaming of the luminous matter is only poorly indicated because distance determination independent of the Hubble law is too uncertain. Very accurate distance tracers, ±5%, are available in the Type Ia Supernovae, but they have been too sparsely observed to be useful in this context. Detection with GAIA followed by ground-based monitoring can give distances of about 50 000 supernovae out to 500 Mpc or $z = 0.10$. This will greatly enhance our knowledge of the structure and velocities of the Universe. The underlying dark matter and dark energy will emerge from obscurity.

1 The velocity field of galaxies

The current picture of the large scale distribution of galaxies shows walls of galaxies separating large voids of space with very few galaxies (see Strauss 1998). A proper dynamical interpretation of this picture would greatly profit from a direct knowledge of the velocity field, which is presently confused by the indirect derivation of the distances by means of an assumed uniform Hubble expansion. Radial velocities of galaxies are simply transformed into distances by means of a uniform Hubble expansion.

Independent distance determinations are available (Tully-Fisher and Fundamental Plane) but are quite uncertain, ±20%, so that our knowledge of deviations from the uniform Hubble flow is scant. We know from de Vaucouleurs (1958) that deviations do exist.

A very accurate distance indicator is available in the Type Ia supernovae (SN) because their absolute luminosity is a tight function of the light curve.

A typical distance accuracy of 5% for a single object can thus be obtained (Riess et al. 1996).

This method could be used if a large number of SNe could be detected and their decline be followed photometrically. This is possible by a combination of Gaia detections of thousands of SNe and groundbased follow-up of the light curves and radial velocity measurement.

2 Detection of supernovae

The light curves and the absolute luminosities of Type Ia SNe have been studied by Hamuy et al. (1996). Their Fig. 9 shows that M_V and M_I at maximum are about -19.0 and -18.8 mag, respectively, assuming $H_0 =$ 65 km/s/Mpc. Nearly all SNe in this figure have $M_V < -18.5$ mag during the 15 day interval from $t = -5$ to $+10$ days since the B maximum. These are called young SNe hereafter. M_I is typically brighter than -18.5 mag during 25 days (from $t = -5$ to 20 d) while M_V falls off more rapidly. If a young SN is detected and monitored in B, V for about 40 days an accurate absolute magnitude and distance can be derived.

The rate of all types of SNe is given by Jørgensen et al. (1997) Fig. 5. It is 300 yr^{-1} with an uncertainty about a factor 2 for a maximum of apparent red magnitude $R < 15$ mag. Allthough the authors use a different value of $H_0 = 75$ km/s/Mpc this rate as function of apparent magnitude remains valid for our case because the authors assume the same absolute magnitudes of SNe. For our value $H_0 = 65$ km/s/Mpc, $R < 15$ mag and $M_R = -19$ the distance modulus of $m - M < 15 + 19 = 34$ corresponds to $d = 63$ Mpc.

The rate of SNe within d Mpc is then

$$N = 300(d/63)^3 \quad [yr^{-1}] \tag{1}$$

at least for SNe with red magnitude $R < 20$.

The sky mappers in the two Astro telescopes on GAIA (Høg et al. 1999) will detect all stars brighter than R=20.0 mag. The stars are then measured on 17 CCDs in the remaining part of the astrometric field. These repeated measurements allow a safe rejection of all false detections due to any kind of noise, and they allow a decision whether it is a moving object, i.e. a minor planet. This results in a detection of objects with $M_R = -18.5$ at distances out to $d = 500$ Mpc corresponding to $z = 0.11$. The rate of SNe in this volume is $N = 150\,000$ per year. About 80% of these are Type Ia, and the rest is Types Ib and II.

The spin axis of GAIA revolves about the sun in 72 days at a fixed angle from the sun of 55 deg. The spin axis has a constant velocity of 0.17 deg/hour = 61 deg/15 d. This means that about 30% of the sky is observed in 15 days. Thus, 30% of all young SNe with $R_{max} < 19.5$ mag will be detected by GAIA not later than 10 days after the maximum.

The expected number of young Type Ia SNe detected during a 4 year observing period of GAIA and observable from the ground is

$$N = 150\,000 \times 0.80 \times 4 \times 0.30 \times 0.75 \times 0.5 \simeq 54\,000 \qquad (2)$$

where the factor 0.75 accounts for the invisibility of galaxies and SNe in a belt of 30 deg width centred on the Galactic equator, and the factor 0.5 takes into account that some are too close to the sun to be followed from the ground for the required time of about 40 days.

The total number of SNe selected from GAIA observations alone will be about twice as high, including the other types than Ia and the old ones.

3 Ground-based work

Finding bright SNe at an unprecedented rate has just started with the Katzman Automatic Imaging Telescope (KAIT), a robotic 76-cm reflector at Lick Observatory (Sky & Telescope, January 1999, 26). It goes through the observable part of a list of 5000 target galaxies every week at a rate of 80-90 galaxies per hour. The CCD camera can reach down to 19.5 mag with a 30 second exposure. Since a galaxy typically produces one SN in 100 years the expected detection rate is 20-30 SNe/year. This rate is at least two orders of magnitude less than that of GAIA, which is not expected to be reached by any ground- or space-based instrument in the forseeable future.

Ground-based photometry of a SN must be started a few days after the GAIA observation, thus calling for a quick photometric reduction of GAIA observations and a quick response by ground-based observers.

All GAIA detections of a point source must be checked. It is utilized that a star will appear in the other Astro telescope within a couple of hours due to the overlap of consecutive scans. A comparison with all previous GAIA observations of the same position on the sky will be used to decide whether the star is new. A data base with epoch photometry from the first 12 months of mission should be sufficient to discriminate against most variable stars, especially since the Galactic latitude is required to be larger than 15 deg. An inspection or automatic comparison with a digital sky survey might be used to verify the presence of the parent galaxy, but this is not applicable to the faintest SNe with existing sky surveys because the galaxies are too faint.

The first ground-based photometric observation should give the $B - V$ colour index. This quantity is typically equal to 0.5 mag at $t = 20$ d (Fig. 3 of Hamuy 1996). A smaller colour index can therefore be used to select the SNe which are good candidates for distance determination and therefore deserve to be followed further by ground-based photometric observations. This colour limit will also discrimate against most variable stars that could appear on the GAIA sky since most variables are of late spectral type. The remaining about 60 000 SNe should be followed for about 40 days with 10 observations each. Altogether about 200 000 observations per year for 4 years are required. Even a smaller observation project would be of great scientific value.

An instrument like the KAIT but with larger aperture about 200 cm would be required for the photometry, in fact an instrument in each hemisphere. The SNe must be followed until they have faded by about 3 mag in B in order to classify the light curve and derive the absolute magnitude, this means observation until $B = 23$ mag. The radial velocity could be obtained from the galaxy and is therefore not bound to be measured immediately after the SN eruption.

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