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INTERSTELLAR REDDENING OF TYPE IA SUPERNOVAE

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Abstract
We re-investigate the Lira-Phillips relation of Type Ia supernovae and its use for determination of reddening of individual SNe Ia. We use a more recent, more extensive dataset of SNe Ia with negligible reddening, and attempt to refine the prediction of the intrinsic B-V color index. We find that the Lira-Phillips relation is valid, but the dispersion of the intrinsic B-V colors is substantial. The present data may suggest slightly redder intrinsic colors, thus, the previously calculated total extinctions (and the corresponding distance moduli) should be decreased by ~ 0.19 mag.

Keywords: *supernovae: general, interstellar reddening*

1 Introduction

Type Ia supernovae (SNe) have been succesfully used as distance indicators, even to cosmological distances, due to their extreme brightness (Perlmutter et al. (1999), Riess et al. (2004)). Although their peak luminosities have significant dispersion, there is a relation between the peak luminosity and the decay rate of the light curve. This makes it possible to calibrate the luminosity of a given SN from its observed light curve, and reduce the light curve dispersion. In order to do so, one needs i) a large sample of SNe with independently known distances, observed in the same photometric system, and ii) information about all the effects that distorts the photons coming from the SNe while reaching the

Earth. One of the most important effects is due to the presence of interstellar dust: interstellar reddening (and extinction). Unfortunately, the measurement of reddening is quite difficult, mostly because our knowledge about the distribution and characteristics of dust in other galaxies is limited. It is usually assumed that the extragalactic dust has similar properties as that in the Milky Way, i.e. the total light absorption is related to the selective absorption via the galactic reddening law: $A_V = 3.1 \cdot E(B-V)$, and the selective absorption in different colors have the same ratio as in the Milky Way.

2 Determination of supernova reddenings

Reddening of supernovae has two components: $E(B-V)_{Gal}$ is caused by the dust present in our galaxy along the line of sight, $E(B-V)_{Host}$ is the result of the dust of the supernova's own galaxy. The first one can be relatively easily determined thanks to the reddening map of the Milky Way Galaxy made by Schlegel et al. (1998).

Obtaining host galaxy reddening values is considerably more complicated. Fortunately, SNe Ia do not occur in dense, dusty environment (unlike Type II SNe) indicated by the absence of lines originated from circumstellar matter in the spectra of SNe Ia. Thus, the reddening of SNe Ia is usually caused by the dust distributed along the line of sight.

To illustrate this general picture, we have computed a Monte Carlo simulation of the distribution of the reddening of SNe Ia. We have defined a model galaxy with similar (exponential) dust distribution such as in the Milky Way, and placed SNe randomly within the galaxy. The model galaxy has been put at random positions and distances with random inclination, and it was "observed" through the dust projected into the line of sight. Computing the total reddening both the dust in the Milky Way and in the host galaxy has been taken into account.

Fig. 1 shows the computed apparent magnitudes of model SNe Ia (open circles) with the observed data (SNe Ia before 2002) against the distance. The line indicates the true distance modulus of a fiducial SN Ia as a function of distance when there is no interstellar extinction. The distribution of the observed and computed points are very similar. This means that the scattering of the observed data in Fig.1 can be reasonably explained by interstellar extinction that varies from SN to SN.

If we had a large sample of *observed* SNe Ia, we could estimate the expected value of the reddening statistically, using the distribution in Fig. 1. However, in

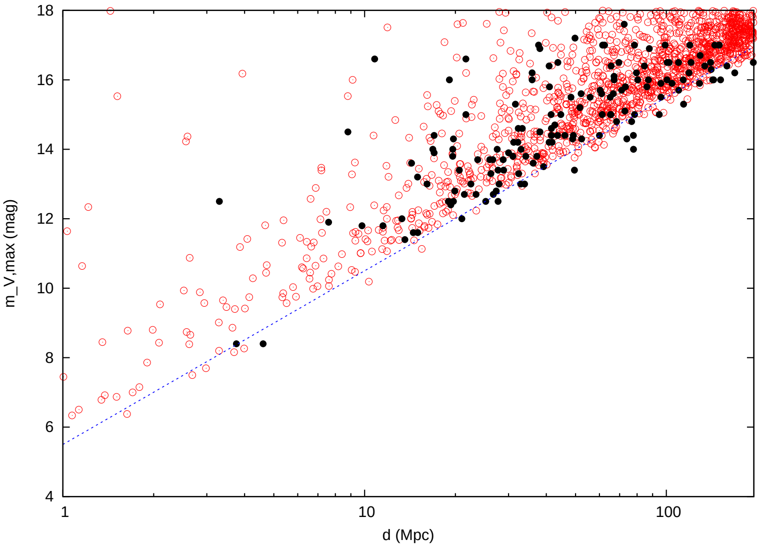

Figure 1: *Apparent magnitudes as a function of distance. Filled circles represent the observed data while the open circles are from the Monte Carlo simulation. The dotted line describes the extinction-free magnitude - distance relation (i.e. the true distance modulus) for SNe Ia with constant peak brightness. It is visible that the observed and computed data have the same distribution, thus, the dispersion of the observed data is mostly due to interstellar extinction.*

reality, such observational sample is not at our disposal. Therefore, it is important to determine the reddening of individual SNe directly from observations.

There are several methods to estimate individual reddenings. One is based on direct spectroscopic measurement of interstellar Na I D lines (Munari & Zwitter (1997)). The Multi-Color Light Curve Shape (MLCS) method (Riess et al. (1996)) determines the reddening of SNe Ia by comparing the observed magnitudes with template light curves. This method is based on the empirical correlation between the intrinsic color and the light curve shape of SNe Ia. The third method is the Lira-Phillips relation (Phillips et al. (1999)) that will be presented in detail in the next section.

2.1 The Lira–Phillips relation

Phillips et al. (1999) demonstrated that the $B-V$ color curves of SNe Ia that suffered negligible interstellar extinction evolve in an impressively similar fashion between $30-90$ days after their maximum light (measured in V filter). During this interval the $B-V$ color evolution seems to be independent of light curve shape and decline rate (which is connected with the similarity of the spectra at these phases). Thus, measuring the $B-V$ curve of a reddened SN Ia and comparing it with the expected color evolution, one can get good constraints on the amount of interstellar reddening for a particular SN.

Since it is a purely empirical method, it must be calibrated empirically. One needs many unreddened SNe Ia in order to get a fiducial $B-V$ curve between $30 \leq t \leq 90$ days. Phillips et al. (1999) applied three basic criteria for selecting such SNe:

1. the absence of interstellar Na I and Ca II lines in the spectra
2. the Hubble-type of the host galaxy is E or S0
3. the Hubble-type of the hist galaxy is S or SB, but the SN is located outside the spiral arms and dust lanes in the disk.

These criteria resulted in four SNe (1992A, 1992bc, 1992bo, 1994D) that Pillips et al. (1999) could use for calibration. The least-squares fit to their observed colors gave the following result for $30 \leq t \leq 90$ days past V maximum:

$$(B-V)_0 = 0.725 - 0.0118(t_V - 60), \tag{1}$$

where t_V is the elapsed time (in days) since V maximum.

2.2 Improving the Lira-Phillips relation

Since 1999 many more SNe Ia have been discovered, observed and published. Thus, it may be possible to improve the Lira-Phillips relation based on these more recent data. We have surveyed the literature and collected the data of potential SNe Ia. The original selection criteria listed above have been supplemented by a new one: the reddening is assumed to be negligible if it was below 0.03 according to the MLCS method (which is less than the uncertainty of the reddening determination in this method). These criteria resulted in the selection of 10 more SNe Ia beside the 4 one used by Phillips et al. (1999). The names and the basis of their selection are listed in Table 1.

Table 1: *The selected sample of SNe Ia with negligible reddening. The applied selection criteria are indicated in columns 2 - 5.*

SN	Selection criteria				References
	Morphology of host	Position of SN in host	Spectrum	MLCS	
1992A		+	+		1
1992bc		+	+		2
1992bo		+	+		2
1994D		+	+		1, 3, 4, 5
1992al		+		+	2
1993ae	+			+	6, 7
1995D	+		+		1, 6, 7
1996X	+		+		6, 8
1997cn	+			+	9, 10
1998de	+		+		9, 11
1998dx		+		+	9
1999ej	+			+	9
2000dk	+			+	9
2003du		+	+		12

References: (1) Altavilla et al. (2004), (2) Hamuy et al. (1996), (3) Richmond et al. (1995), (4) Patat et al. (1996), (5) Tsvetkov & Pavlyuk (1995), (6) Riess et al. (1999), (7) Ho et al. (2001), (8) Patat et al. (1996), (9) Jha et al. (2006), (10) Turatto et al. (1998), (11) Modjaz et al. (2001), (12) Anupama et al. (2005)

The color curves of the selected SNe are plotted in Fig. 2. A least squares fit to the same data range as above resulted in

$$(B-V)_0 = 0.781 - 0.0122(t_V - 60). \tag{2}$$

This new relation has essentially the same slope as the original one (Eq. 1), but a slightly higher constant term.

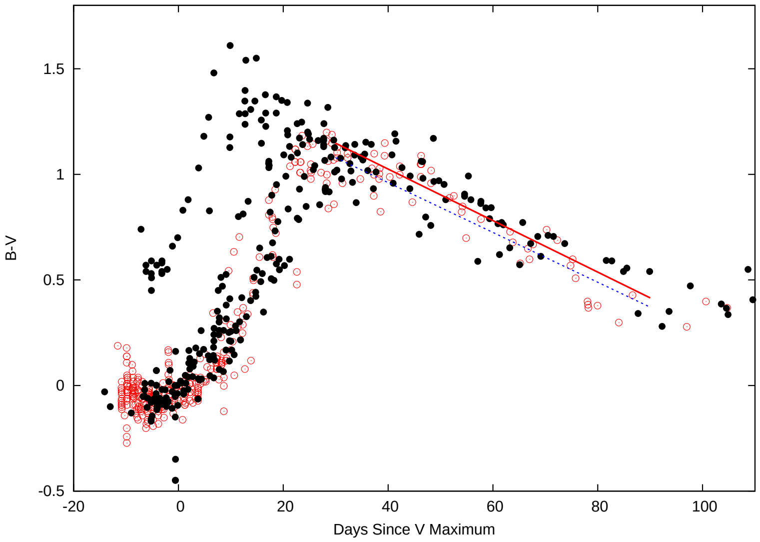

Figure 2: *B-V color evolution of the selected SNe. Open circles indicate the data used originally by Phillips et al. (1999), while filled circles represent the additional SNe (see Table 1 for references). The dashed line is the original relation (Eq. 1) and the solid line is the new calibration (Eq. 2).*

3 Discussion

From Fig. 2 it is visible that the new observational data of reddening-free SNe Ia confirm the existence of the Lira-Phillips relation. However, the data show considerable scatter (~ 0.3 mag) in the $30 \leq t \leq 90$ days interval that cannot be attributed purely to observational noise. This dispersion is significantly lower than during the early phases of the evolution of SNe Ia, thus, the original idea of the Lira-Phillips relation is still valid. But the $(B-V)$ color evolution of SNe Ia is clearly not as homogeneous as it was previously thought. There is a dispersion from SN to SN that causes a ~ 0.3 mag overall uncertainty in the intrinsic $(B-V)$ color, that propagates further into the reddening determination.

Based on the available data, the new relation (Eq. 2) predicts an intrinsic $(B-V)$ that is 0.06 mag redder than the one based on the original relation (Eq. 1). From the standard reddening law this corresponds to $\Delta A_V \sim 0.19$ mag increase of the extinction in the V band. If this is indeed true, then the SNe Ia distance moduli that have been determined assuming the reddenings from Eq. 1, must be decreased by about 0.19 mag. It may also affect the calibration of the MLCS method, since it is based on individual reddenings such as those from the Lira-Phillips relation. Since many of the high-z SNe distances are based on the MLCS method, a reddening correction might further incorporate into the cosmological distances. However, this correction is not significant at present, because the difference between Eq. 1 and 2 is well below the 0.3 mag dispersion discussed above. Many more SNe Ia are needed to refine the reddening-free sample and further clarify this important issue.

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