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Authors
Benítez, Narciso
Riess, Adam
Nugent, Peter
et al.

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THE MAGNIFICATION OF SN 1997ff, THE FARTHEST KNOWN SUPERNOVA

Narciso Benítez[1], Adam Riess[2], Peter Nugent[3], Mark Dickinson[2], Ryan Chornock[4], and Alexei V. Filippenko[4]

ABSTRACT

With a redshift of $z \approx 1.7$, SN 1997ff is the most distant type Ia supernova discovered so far. This SN is close to several bright, $z = 0.6 - 0.9$ galaxies, and we consider the effects of lensing by those objects on the magnitude of SN 1997ff. We estimate their velocity dispersions using the Tully-Fisher and Faber-Jackson relations corrected for evolution effects, and calculate, applying the multiple-plane lensing formalism, that SN 1997ff is magnified by 0.34 ± 0.12 mag. Due to the spatial configuration of the foreground galaxies, the shear from individual lenses partially cancels out, and the total distortion induced on the host galaxy is considerably smaller than that produced by a single lens having the same magnification. After correction for lensing, the revised distance to SN 1997ff is $m - M = 45.5$ mag, which improves the agreement with the $\Omega_M = 0.35, \Omega_\Lambda = 0.65$ cosmology expected from lower-redshift SNe Ia, and is inconsistent at the $\sim 3\sigma$ confidence level with a uniform gray dust model or a simple evolution model.

Subject headings: cosmology: observations — cosmology: cosmological parameters — gravitational lensing — supernovae: general — supernovae: individual (SN 1997ff)

1. INTRODUCTION

One of the strongest lines of evidence for an accelerating universe is the observation that $z \approx 0.5$ type Ia supernovae (SNe Ia) are ~ 0.25 mag fainter than predicted by an $\Omega_\Lambda = 0$ cosmology (Riess et al. 1998; Perlmutter et al. 1999; Riess 2000). However, there are several effects such as gray dust (Aguirre 1999) or luminosity evolution (Drell, Loredo, & Wasserman 2000) that could mimic the effect of a cosmological constant.

Riess et al. (2001, hereafter R2001) have recently concluded that SN 1997ff, one of the two SNe discovered by Gilliland, Nugent, & Phillips (1999) in the Hubble Deep Field North (HDFN; Williams et al. 1996), has a redshift of $z \approx 1.7$, making it the highest redshift probable SN Ia identified so far. (The SN Ia classification is based on the nature of the host galaxy, an evolved, red elliptical; also the observed colors and temporal evolution of SN 1997ff are most consistent with those of SNe Ia.) This object is particularly interesting because at $z > 1$ the preceding epoch of deceleration causes objects to appear brighter than a persistence of astrophysical effects invoked as alternative hypotheses to explain the SN Ia faintness at $z \approx 0.5$. R2001 measured a distance modulus for SN 1997ff which is more than a magnitude brighter (1.25 ± 0.32 mag brighter assuming the spectroscopic indication of $z = 1.755$) than the predictions from uniform gray dust or toy evolution models, disfavoring these alternatives to a cosmological constant.

Lewis & Ibata (2001) stated that SN 1997ff could be magnified by a factor of ~ 1.4 by two "elliptical systems" close to its line of sight. R2001 anticipated a magnification of 0.3 mag from these same sources, in good agreement with Lewis & Ibata. As we see below, these are in fact two spiral galaxies (#709 and #720 in Table 1) which magnify SN 1997ff by only ~ 0.2 mag, about half of the value estimated by Lewis & Ibata, and close to the upper limit inferred by R2001 for these two galaxies from the induced shear on the host-galaxy shape and orientation.

Mörtsell, Gunnarsson, & Goobar (2001) also tackled this problem using rest-frame B-band and ultraviolet luminosities to infer the masses of the lenses. After performing numerous ray-tracing simulations, they concluded that the range of possible magnifications was too large to obtain a firm value for the distance modulus of SN 1997ff based on our current knowledge of the lensing galaxies.

Here we use the superb photometric and positional information provided by the HDFN to estimate velocity dispersions for the galaxies lensing SN 1997ff using the Tully-Fisher (TF) and Faber-Jackson relations, and correcting for evolution effects. With this information, we calculate, using the multiple-plane lensing formalism (Schneider, Ehlers, & Falco 1992, hereafter SEF), the magnification of SN 1997ff and the shear induced on the host galaxy, which is fully compatible with its expected intrinsic shape.

The structure of the paper is as follows. Section 2 describes the environment of SN 1997ff, and identifies the main lensing foreground galaxies. The multiple-plane lens formalism is discussed in § 3, while § 4 presents our estimates of the magnification and shear. Section 5 summarizes our main results and conclusions.

2. THE LENSES

Figure 1 shows the positions of the galaxies around SN 1997ff with $I_{814W} < 27$ mag and $r < 15''$. The coordinates, ID number, and I_{814W} magnitudes are taken from the Fernández-Soto, Lanzetta, & Yahil (1999) catalog and photometric redshifts have

[1] Department of Physics and Astronomy, The Johns Hopkins University, 3400 N. Charles Street, Baltimore MD 21218, txitxo@pha.jhu.edu
[2] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218
[3] Lawrence Berkeley National Laboratory, Berkeley, CA 94720
[4] Department of Astronomy, 601 Campbell Hall, University of California, Berkeley, CA 94720-3411

been obtained using the BPZ package (Benítez 2000, http://acs.pha.jhu.edu/~txitxo/bpz.html). Table 1 lists the characteristics of the galaxies contributing significantly to the magnification of SN 1997ff. The B and I absolute magnitudes M_B and M_I have been estimated from the I_{814W} and *HST*/NICMOS F110W and F160W magnitudes, respectively. This was done by generating K-corrections based on their spectral type, drawn from the 4 main Coleman, Wu, & Weedman (1980) galaxy types and two Kinney et al. (1996) starbursts; the K-corrections are $\lesssim 0.4$ mag in the case of the four strongest lenses.

The circular velocities V_c for the late-type galaxies in Table 1 have been estimated using the recent results of Ziegler et al. (2002), which measure the B-band TF slope and normalization for $R < 23$ mag, $0.5 < z < 1$ FORS deep field galaxies — quite similar, in statistical terms, to our lens sample. We assume a relative error of $\delta V_c/V_c \approx 1/3$ estimated from the scatter around the best fit in Figure 3 of Ziegler et al. (2002). These errors are propagated in the calculation of the Einstein radius, etc., and account for most of the uncertainty in the final value of the magnification. As a cross-check, we have also estimated the expected values of V_c usingthe I-band TF relation, as determined by Giovanelli et al. (1997): the results are very similar to those of the Ziegler et al. (2002) B-band TF.

To determine their circular velocities with another method, we observed galaxies #709 and #720 on 2001 May 29 and 30 UT with the Echellette Spectrograph and Imager (ESI; Sheinis et al. 2002) on the Keck-II 10-m telescope. A slit width of $1''$ was chosen, which gave an instrumental resolution of ~ 70 km s^{-1} (based on fits to the night-sky emission lines). The spectrum of galaxy #709 shows strong, single-component emission lines with FWHM = 78 km s^{-1} (corrected for the instrumental resolution). The spectrum of galaxy #720 exhibits double-peaked emission-line profiles, with a peak-to-peak splitting of 200 km s^{-1}. After correcting for the assumed inclination angles (34° for galaxy #709 and 69° for galaxy #720), we derive circular velocities of 70 and 110 km s^{-1}, respectively. In contrast, the respective circular velocities expected according to the TF relation are substantially higher, $\sim 136 \pm 48$ and $\sim 175 \pm 60$ km s^{-1} (Table 1). Although both values are marginally consistent at the $\sim 1.25\sigma$ level, these results, especially in the case of #709, seem to support the conclusion of Gillespie & van Zee (2002) that emission lines from the central regions of star-forming galaxies can underestimate the total circular velocity by a factor of ~ 2. Hence, we consider the circular velocities derived from the Keck data to be lower limits on the true quantities, and we use the TF estimates and their uncertainties in the calculations below. Taking the spectroscopic results at their face value would yield $\Delta\mu = 0.07$ mag from the #709–#720 pair alone, which can be considered to be the lower limit on the magnification of SN 1997ff. Note also that this would make the total magnification smaller (by ~ 0.16 mag), and would further strengthen our cosmological conclusions on gray dust or evolution models.

For the two early-type galaxies, #694 and #653, we use the Faber-Jackson relation between the halo velocity dispersion and the B_J-band luminosity as defined by Kochanek (1994, 1996), $\sigma_{DM} = (225 \pm 22.5)(L/L_*)^4$, where L_* corresponds to $B_J = -19.9 + 5\log h$ mag (Efstathiou, Ellis, & Peterson 1988) and $h = H_0/(100$ km s^{-1} Mpc^{-1}). Owing to the redshift of these galaxies, $z \approx 0.9$, we expect evolution effects to be considerable (e.g., Treu et al. 2002; although see also Crampton et al. 2002). Keeton, Kochanek, & Falco (1998) studied the properties of a sample of 17 lensing galaxies with $0.1 < z < 1$, and measured an evolution rate for the mass-to-light ratio of $d\log(M/L_B)/dz \approx -0.6 \pm 0.1$ for the cosmological model considered here. After accounting for this effect, the velocity dispersions of galaxies #694 and #653 become about half of their value in the absence of evolution.

3. THE LENSING EQUATIONS

Because of the configuration of the lenses, placed at different redshifts, it is necessary to use the multiple lens-plane formalism (SEF) to estimate the magnification and shear on the SN 1997ff position. The magnification matrix for N lenses at, in general, different positions and redshifts, can be represented as

$$A = I - \sum_{i=1}^{N} A_i, \qquad A_j = I - \sum_{i=1}^{j-1} \beta_{ij} U_i A_i, \tag{1}$$

where $A_1 = I$ (the identity matrix), the coefficients β_{ij} are distance ratios ($\beta_{ij} = 0$ if all the galaxies are on the sample plane), and U_i can be represented as

$$U_i = \kappa_i I + \gamma_i \begin{pmatrix} \cos 2\phi_i & \sin 2\phi_i \\ \sin 2\phi_i & -\cos 2\phi_i \end{pmatrix}.$$

In this equation κ_i and γ_i correspond to the convergence and shear induced by each i-galaxy on the source in the absence of other lenses. Assuming that the mass distribution of the galaxies can be well represented by a singular isothermal sphere, we have

$$\kappa_i = \frac{\theta_{ei}}{2\theta_i}, \qquad \gamma_i = -\frac{\theta_{ei}}{2\theta_i} e^{i2\phi}.$$

The Einstein radius θ_{ei} can be represented as $\theta_{ei} = 4\pi(V_c/c)^2 D_{is}/D_s$ (Bartelmann & Schneider 2001), where V_c is the circular velocity, D_{is} the distance between the i-galaxy and the source, and D_s is the distance between the source and the observer. Finally, if the matrix A is symmetric, it can be represented in the usual way as

$$A = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & \kappa \end{pmatrix},$$

where the total shear is $\gamma = \gamma_1 + i\gamma_2$ and the total magnification is $\mu = [(1-\kappa)^2 + \gamma^2]^{-1}$.

To describe the effects of lensing on the shape of a galaxy, we can represent it with the complex ellipticity $\chi = [(1-q^2)/(1+q^2)]e^{i2\phi}$, where $q = a/b$ is the axis ratio, $0 < q < 1$. Given a reduced shear $g = \gamma/(1-\kappa)$, the intrinsic ellipticity of the source can be recovered as (Schneider & Seitz 1995)

$$\chi_s = \frac{2g + \chi + g^2\chi^*}{1 + |g|^2 + 2Re(g\chi^*)}.$$

The above equations have been implemented as a Python module which can be obtained by contacting N. Benítez.

4. RESULTS

4.1. *The Magnification*

Using the above expressions, we find that the lensing correction to the brightness of SN 1997ff is a magnification of $\Delta m_\mu = 0.34 \pm 0.12$ mag, for an $\Omega_M = 0.35$, $\Omega_\Lambda = 0.65$ cosmology and using the filled-beam approximation to the angular distance. Table 1 shows the Einstein radius and magnification μ_i induced on the position of SN 1997ff by each individual galaxy. If we naively multiply all these magnifications, we arrive at a value of $2.5 \log(\Pi_i \mu_i) = 0.31$, which represents only a 10% difference from the multiple lens-plane formalism result.

4.2. *The Host Ellipticity*

R2001 estimated that, from the ellipticity and orientation of the host galaxy, the probability of its being magnified by more than 0.34 mag by the galaxy pair #709 and #720 (the two strongest lenses) is only 18%. Our new result for the total shear is $\gamma = 0.084$, half of the value expected for an equivalent single isothermal sphere, and along the direction perpendicular to the #709 + #720 pair. Given this reduced shear, the host ellipticity is significantly less constraining in providing an upper limit to the magnification; the 90% confidence limits for the magnification are (0.086, 1.37). The cause of this reduced leverage of the distortion constraint is that the shear vectors from the galaxies whose contribution was not considered in R2001 partially cancel out. The result is that, unlike the magnification (~ 0.13 mag), the distortion they induce on the SN 1997ff host is very small, and slightly counteracts that caused by the #709 + #720 pair, further reducing the total shear.

4.3. *Cosmological Constraints*

R2001 measured a distance modulus of $m - M = 45.15 \pm 0.32$ mag, assuming $z_s = 1.755$. After correction for lensing, the new value is $m - M = 45.49 \pm 0.34$ mag, in excellent agreement with the expected value of 45.68 mag for the $\Omega_M = 0.35, \Omega_\Lambda = 0.65$ ($h = 0.65$) universe expected from the $z \approx 0.5$ population of SNe Ia (Riess et al. 1998).

Using the preceding calculation to correct the SN 1997ff distance modulus for lensing, we can compare the result to toy models that invoke astrophysical sources of dimming instead of a cosmological constant to match the observations of SNe Ia at $z \approx 0.5$. Here we will assume the spectroscopic redshift measurement of $z = 1.755$ for SN 1997ff to simplify the evaluation of the astrophysical dimming expected at a specific redshift. The astrophysical dimming described in R2001 would take the functional form of $0.3z$ mag relative to an empty Universe. At $z = 1.755$ this results in a predicted distance modulus of $\sim$46.4 mag ($h = 0.65$). The lensing-corrected distance modulus of SN 1997ff is 45.49 mag, smaller (i.e., the SN is brighter) than the astrophysical dimming model by 0.91 mag (reduced from 1.25 mag without the lensing correction). As discussed by R2001, the fit to the SN data yields non-Gaussian and asymmetric uncertainties beyond the 2σ interval. Returning to the fit from R2001 to the SN data (corrected by the slight increase in the distance modulus error due to the lensing uncertainty) yields confidence intervals in the direction of larger distances of $+1\sigma$, $+2\sigma$, and $+3\sigma$ equal to 0.34, 0.67, and 0.90 mag, respectively. We therefore conclude that the simplest alternatives to an accelerating universe appear to be inconsistent with SN 1997ff at the 3σ confidence level. However, we caution that the astrophysical model of dimming is naive and before tests of astrophysical sources can be considered robust, independent confirmation of this result will be required from additional SNe Ia at $z > 1$.

Mannheim (2001) has shown that the observations of $z < 1$ SNe can be accommodated within a conformal gravity cosmological model (Mannheim 1992) with $q_0 = -0.37$, which predicts a distance modulus of $m - M = 46.11$ at $z = 1.755$. This agrees within 1.8σ with our new result, implying that more data are necessary to discriminate between this hypothesis and a cosmological constant.

5. DISCUSSION

The magnification of SN 1997ff, $\mu \approx 1.4$, is high but compatible with the expectation from simulations. For instance, Barber et al. (2000) find $\mu > 1.4$ for 5% of the lines of sight to $z = 2$. However, we would not attribute such magnification to a selection effect; the dispersion of observed magnitudes due to lensing is only $\sim$0.2 mag, no larger than the intrinsic dispersion of SNe Ia, and it has been shown to cause negligible selection bias (Riess et al. 1998).

It is unlikely that lensing by large-scale structure could significantly affect our results. Dalal et al. (2002) show that most of the scatter in the magnification comes from scales of less than $1'$, corresponding to the range considered here. The expected residual root-mean-square on larger scales is ~ 0.07 mag, smaller than our uncertainty. It is noteworthy that by combining an "individual lenses" approach like the one followed here, with a shear analysis which estimates the large-scale magnification as proposed by Dalal et al., it could be possible to significantly reduce the uncertainty in supernova distances due to lensing. Dark haloes (without optically visible galaxies) may be a possible problem with this approach, but so far there is very little, if any, evidence for their existence. The major source of error in our calculations is the dispersion in the TF and Faber-Jackson relations at high redshift, but in the future improved calibrations using near-infrared data should reduce this scatter considerably.

The amount of magnification we expect for SN 1997ff is similar to the values determined by Lewis & Ibata (2001) and R2001, and roughly agrees with the results of Mörtsell et al. (2001) for realistic values of their input parameters. However, our use of the multiple lens-plane formalism, individual galaxy K-corrections, and TF and Faber-Jackson relationships, corrected for evolution, provides an estimate that is more accurate and robust than previous work.

In summary, SN 1997ff, with $z \approx 1.7$, is the highest redshift SN Ia discovered so far. It is shown here that gravitational lensing by nearby foreground galaxies is likely to have magnified SN 1997ff by 0.34 ± 0.12 mag. Due to the spatial configuration of the foreground galaxies, the shear from the individual lenses partially cancels out, and the total distortion induced on the host galaxy is less than half of that produced by a single lens with the same magnification. After correcting for lensing, and assuming $z_s = 1.755$, the distance modulus to SN 1997ff is

$m - M = 45.49 \pm 0.34$ mag, in better agreement with the $\Omega_M = 0.35, \Omega_\Lambda = 0.65$ cosmology expected from lower-redshift SNe Ia, but inconsistent with uniform gray dust or simple evolution models as an explanation for the dimming of $z < 1$ SNe Ia at the 3σ confidence level. It is noteworthy that our new result also agrees within 1.8σ with the predictions of conformal gravity cosmological models (Mannheim 2001).

Since the study of high-z SNe Ia cannot avoid the effects of gravitational lensing, future use of SNe to constrain cosmological parameters will need to consider and ultimately contend with the effects of lensing.

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Table 1

Galaxies magnifying SN 1997ff ($\Omega_M = 0.35$, $\Omega_\Lambda = 0.65, h = 0.65$)

ID[a]	HDF-ID[b]	X[c]	Y[c]	R[c]	z_s[d]	m_I[e]	m_H[f]	M[g]	Sp. type[h]	V_c	μ[i]	θ_e[j]
709	4-402.32	−0.53	2.98	3.03	0.555	21.68	21.34	−20.14	SB2	136 ± 48	1.106	0.30
650	4-430.0	−0.29	−4.53	4.54	0.875	23.42	23.07	−19.71	SB2	114 ± 40	1.031	0.14
720	4-402.31	0.91	5.29	5.37	0.557	21.01	20.00	−20.75	Sbc	175 ± 61	1.097	0.50
694	4-493.0	6.89	−2.39	7.29	0.849	21.66	20.19	−21.60	El	$148 \pm 30.$	1.035	0.25
625	4-378.0	−5.95	−5.44	8.06	1.225	24.17	23.22	−20.18	Im	138 ± 48	1.014	0.11
653	4-254.0	−14.12	1.19	14.17	0.900	22.34	21.14	−21.19	El	131 ± 28	1.013	0.18

[a] ID in the Fernández-Soto, Lanzetta, & Yahil (1999) catalog.

[b] ID in the Williams et al. (1996) catalog.

[c] Angular distance to the SN 1997ff host in arc seconds.

[d] Spectroscopic redshifts from Cohen et al. (2000)

[e] Apparent AB magnitude in the F814W WFPC2 filter.

[f] Apparent AB magnitude in the F160W NICMOS filter.

[g] Vega-based absolute magnitude B_J for ellipticals, B for the others.

[h] Spectral type (see text).

[i] Magnification created by this galaxy at the position of the host without considering the rest of the lenses in the field.

[j] Einstein radius in arcsec.

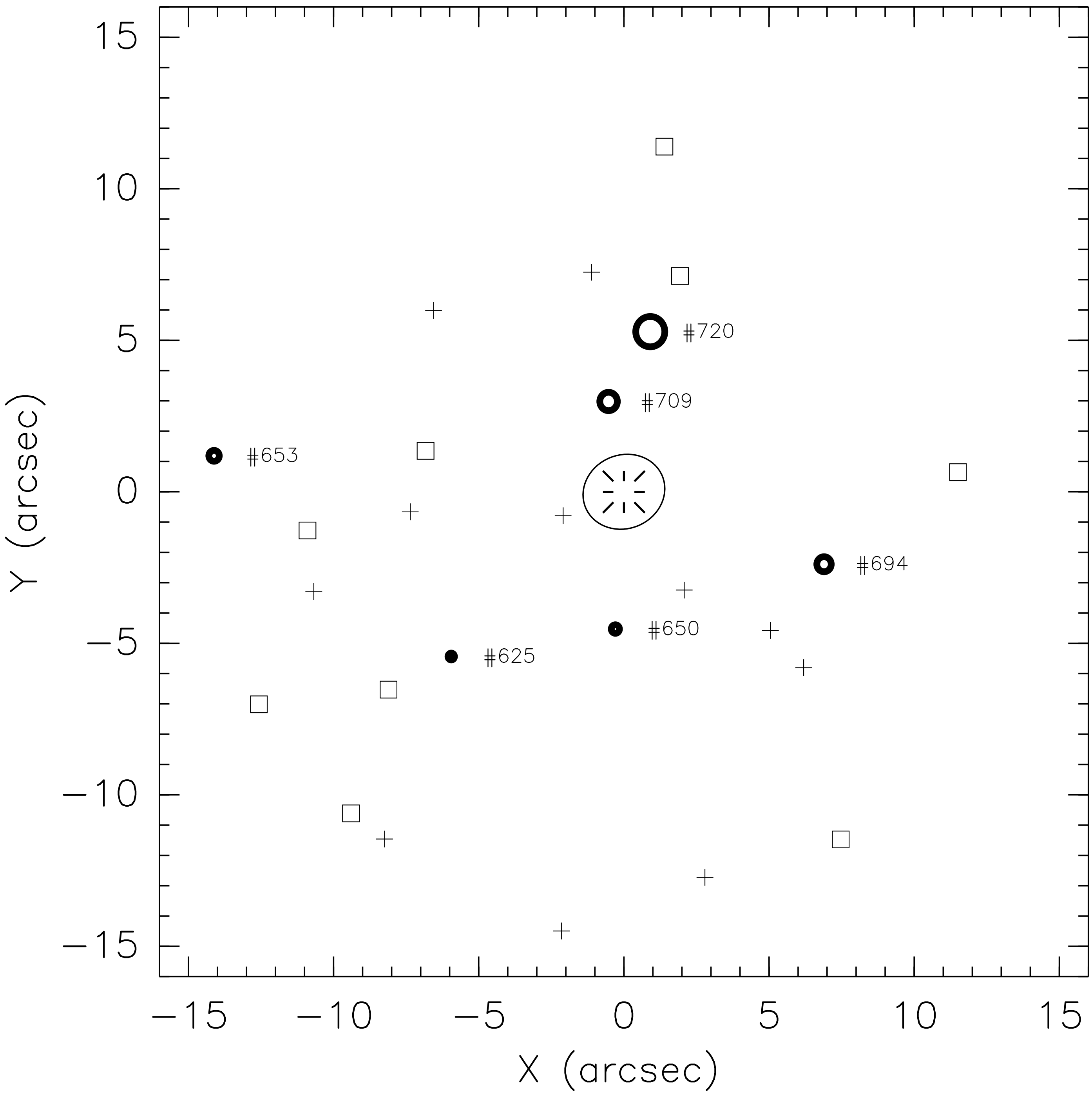

FIG. 1.— The environment of SN 1997ff. The main lenses in Table 1 are represented by circles whose size in proportional to their Einstein radius. The host galaxy is at the center of the plot, with the shape and orientation reported in R2001. Foreground galaxies not massive enough to significantly affect the magnitude of the SN are represented by squares, and crosses correspond to objects with $z \geq 1.7$. North is up and east is to the left.