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Galaxy Groups Associated with Gravitational Lenses and H_0 from B1608+656

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Abstract. Compact groups of galaxies recently have been discovered in association with several strong gravitational lens systems. These groups provide additional convergence to the lensing potential and thus affect the value of H_0 derived from the systems. Lens system time delays are now being measured with uncertainties of only a few percent or better. Additionally, vast improvements are being made in incorporating observational constraints such as Einstein ring structures and stellar velocity dispersions into the lens models. These advances are reducing the uncertainties on H_0 to levels at which the the effects of associated galaxy groups may contribute significantly to the overall error budget. We describe a dedicated multiwavelength program, using Keck, HST, and Chandra, to find such groups and measure their properties. We present, as a case study, results obtained from observations of the CLASS lens system B1608+656 and discuss the implications for the value of H_0 derived from this system.

1. Introduction

The determination of the Hubble Constant from gravitational lenses, first described by Refsdal (1964), is an elegant method that is completely independent from traditional distance-ladder techniques. Recently the uncertainties on lens-based determinations of H_0 have been dropping. Intensive monitoring campaigns have led to precise time-delay measurements (e.g., Kundić *et al.* 1997c; Biggs *et al.* 1999; Fassnacht *et al.* 2002; Burud *et al.* 2002; Hjorth *et al.* 2002). Similarly, high angular resolution imaging from the *Hubble Space Telescope* (HST) or Very Long Baseline Interferometry (VLBI) observations, measurements of the stellar velocity dispersions of lensing galaxies, and improvements in modeling codes have reduced the often large uncertainties due to the lens model (e.g., Treu & Koopmans 2002; Rusin *et al.* 2002; Cohn *et al.* 2001). With uncertainties approaching 10% or less for individual lens systems, it is now necessary to consider other small sources of error in the determination of H_0. In this paper we consider the effect of the environment of the lensing galaxy, namely the contribution of galaxy groups to the lensing potential.

The presence of groups associated with gravitational lenses is not unexpected. In the local Universe, small groups provide the most common galaxy environment (e.g., Turner & Gott 1976; Geller & Huchra 1983; Tully 1987; Ramella *et al.* 1989). Additionally, local elliptical galaxies are preferentially found in dense environments (e.g., Dressler 1980; Zabludoff & Mulchaey 1989). Since most lenses are early-type galaxies, we might expect to find them in groups if the morphology-density relationship continues to moderate redshifts. Theoretical studies have predicted that 25% (Keeton *et al.* 2000) or more (Blandford *et al.* 2001) of lenses should reside in compact groups. The presence of groups associated with lenses has important implications for H_0 determinations. The additional convergence (κ) provided by the group mass will lead to a value of H_0 that is too high if the group contribution is not properly taken into account, i.e.,

$$H_{0,true} = H_{0,meas}(1 - \kappa_{group}).$$

The problem is that the standard lens observables (e.g., image positions and flux ratios) do not provide any indication of the presence of a group; this is the famous "mass-sheet degeneracy" (e.g., Falco *et al.* 1985).

Keeton and Zabludoff (2004) have performed simulations that examine the effect of groups on the measurement of lens properties. Their results on H_0 confirm the effect of the mass-sheet degeneracy. That is, the value of H_0 derived from a lens system *without taking into account the presence of the associated group* is systematically high. Although the large range of values that their simulations produce may be due to the details of their simulations (see comments by Chris Kochanek at this meeting), the fact remains that if the group is not included in the lens model the resulting value of H_0 will be biased high. Also, the effect of the group on the final value of H_0 depends on the individual characteristics of the group. Thus, it appears that it will not be possible to apply a statistical correction for the possible presence of groups associated with lenses. The simulations also show that the input values are recovered more accurately when the group is modeled as individual halos rather than an overall smooth mass distribution. Therefore, it is important to search for groups that may be associated with lens systems and, if such groups are found, measure their properties.

2. A dedicated survey for lens-associated groups

The mass-sheet degeneracy has long been acknowledged as a problem with using lenses to determine H_0 (e.g., Falco *et al.* 1985). Therefore, we have been conducting a systematic search for galaxy groups associated with gravitational lenses. The goal of the program is to determine the group properties and correct for the group contribution to the overall lens potential. For a given lens system, the initial observations consist of multi-color ground-based images of the field containing the lens system. These images are used to select targets for spectroscopy. High-priority targets are those which (1) have colors similar to those expected for early-type galaxies at the lens redshift, and (2) have small projected offsets from the lens system (regardless of color). These targets are then spectroscopically observed with LRIS (Oke *et al.* 1995) and ESI (Sheinis *et al.* 2002) at the Keck Telescopes. The main instrument used is LRIS because of its multislit capability. In order to maximize the number of slits on any given mask, some low-priority targets are also included. The spectroscopic observations are used to produce a redshift distribution for the field which is then searched for spikes that may correspond to groups or clusters. Group candidates are followed up with multi-wavelength observations such as *Chandra* imaging to search

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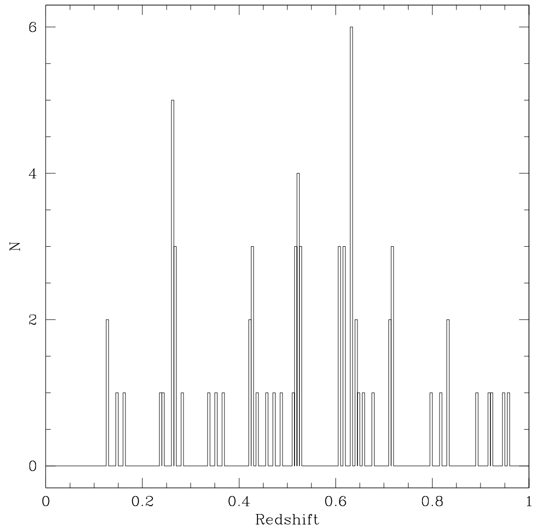

Figure 1. Redshift distribution in the field of B1608+656 (Fassnacht *et al.*, in prep).

for hot intragroup gas and HST imaging to assess the properties of confirmed group galaxies.

3. CLASS B1608+656

The B1608+656 lens system remains the only four-image system for which all three independent time delays have been measured to high precision (Fassnacht *et al.* 2002). New modeling incorporates the Einstein ring seen in HST/WFPC2 images as well as the stellar velocity dispersion of the lensing galaxy. The new model leads to a value of $H_0 = 75^{+7}_{-6}$ km/s/Mpc (Koopmans *et al.* 2003). Furthermore, a 20-orbit multi-band observation of the system with the Advanced Camera for Surveys on HST has been acquired. These deep imaging data will be combined with new software to incorporate fully the Einstein ring data into the lens model. With this wealth of observational information, the B1608+656 system is a natural target for the group-search program.

In order to choose targets for spectroscopic observations, we imaged the B1608+656 field with the Palomar 60-Inch telescope. Images were obtained in three Gunn bands: g, r, and i. Catalogs were created from the images using the SExtractor package (Bertin & Arnouts 1996) and the prioritized target lists were created from these catalogs. Followup spectroscopic observations led to the measurement of approximately 70 galaxy redshifts with the distribution seen in Fig. 1. The largest spike in the redshift distribution is at $z \sim 0.63$, which is the redshift of the lensing galaxy. To test whether this spike represented a good group candidate, we examined the spatial distribution of the galaxies in the spike. The spike members were centrally concentrated around the location of the lens (Fig. 2). Therefore, we consider this as a likely group associated with the lens.

To examine the effect of the group on the value of H_0 derived from B1608+656 we must measure the group properties. As a simple first approximation, we describe the group as a singular isothermal sphere. The velocity dispersion measured from the confirmed group members is 185±63 km/s, which corresponds to a convergence of $\kappa = 0.22/\theta$. Here θ is the distance in arcseconds of the lens system from the group centroid. However,

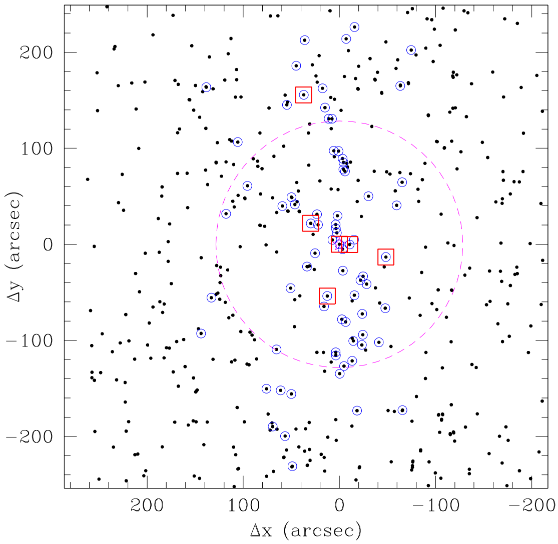

Figure 2. Spatial distribution of the galaxies in the B1608+656 field. Black dots represent galaxies with $r < 23$, open circles represent galaxies with measured redshifts, and open boxes represent galaxies in the redshift spike. The lens system is at the center of the plot at position (0,0). The dashed circle has a radius of 1 h^{-1} comoving Mpc at the redshift of the lensing galaxy. From Fassnacht *et al.*, in prep.

the value of θ is not well determined because different measurements of the location of the group centroid differ significantly. The mean position of the group galaxies and the luminosity-weighted position differ by more than 10 arcseconds, leading to a factor of ∼3 uncertainty in κ_{group} from the centroid position alone. Finding a more accurate group centroid will require significantly more spectroscopy of the field, or a deep X-ray observation to detect the hot intragroup gas. However, the best approach may be to treat the group as a collection of individual halos rather than one smooth overall distribution, as suggested by the simulations of Keeton & Zabludoff (2004). Once again, this will require more spectroscopic followup, but a start can be made with the current data set (Fassnacht *et al.*, in prep.).

4. Other lens-group associations

Through our dedicated survey we have discovered three additional galaxy groups associated with gravitational lenses: a group in the foreground of the CLASS B0712+472 system (Fassnacht & Lubin 2002) and groups associated with CLASS B2108+213 (McKean *et al.*, in prep – see McKean poster at this meeting) and CLASS B1600+434 (Fassnacht *et al.*, in prep). Other spectroscopically-confirmed groups have been detected in association with the lenses PG1115+080 (Kundić *et al.* 1997a), B1422+231 (Kundić *et al.* 1997b; Tonry 1998), MG0751+2716 (Tonry & Kochanek 1999), and MG1113+0456 (Tonry & Kochanek 2000). This list does not include groups discovered by the Zabludoff/Keeton collaboration but not yet reported in the literature, nor the lens systems associated with more massive galaxy clusters (e.g., Q0957+561, RX J0911+0551, RX J0921+4529, SDSS J1004+4112; Young *et al.* 1980; Kneib *et al.* 2000; Muñoz *et al.* 2001; Oguri *et al.* 2004), nor the probable groups for which photometric redshifts exist but spectroscopic confirmation has not yet been acquired (e.g., Rusin et al. 2001; Faure *et al.* 2002). Thus, the

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association of galaxy groups and gravitational lenses provides a rich data set for not only improving the determination of H_0, but also for studying group properties over an interesting redshift range.

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Discussion

ALLOIN: If you had included groups in the southern sky your list of lens-associated groups would have been longer.

FASSNACHT: I was including only groups which have been spectroscopically confirmed. However, I would not be surprised if I missed some groups. It would be unfortunate if they were all in the south.

KOOPMANS: I notice that there are some gaps in the redshift distribution for the B1608+656 field. Do you want to say something about those?

FASSNACHT: I know what you're getting at. However, I don't think that our spectroscopic sampling is dense enough to say anything meaningful yet about the gaps.

KOCHANEK: You can't present the Keeton and Zabludoff simulation results without mentioning the caveats. After many emails with Chuck, I have concluded that the width of the core in their distribution is just due to the uncertainties in the time delays while the broad surrounding distribution is due to the way that they did their simulations.

FASSNACHT: I didn't realize that. However, I think that their main point is still valid – that if you don't include the groups your value of H_0 will be systematically biased high.

WHITE: Our simulations show that you can't approximate most groups as a simple smooth distribution. Instead they show multiple mass peaks. Therefore, it would be better to model the group contribution as coming from the individual halos.

FASSNACHT: I agree. This is something that the Keeton and Zabludoff simulations showed as well. It is definitely something that needs to be done for the B1608+656 group.

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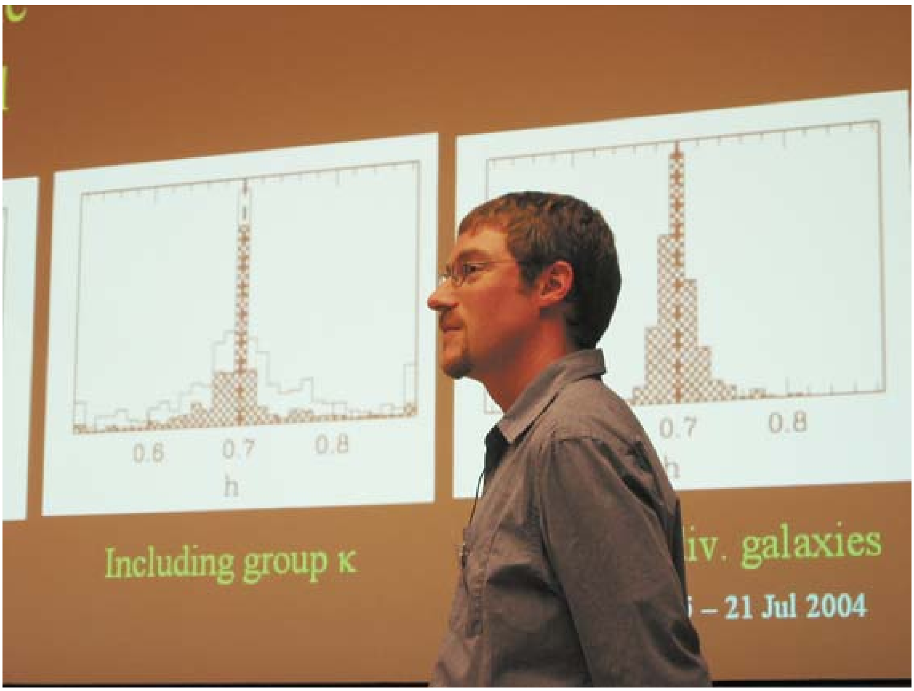

Christopher Fassnacht