The Astrophysical Journal, 504:L23–L26, 1998 September 1

RING STRUCTURE AND WARP OF NGC 5907: INTERACTION WITH DWARF GALAXIES[1]

Zhaohui Shang,[2,3,4] Zhongyuan Zheng,[2,4] Elias Brinks,[5] Jiansheng Chen,[2,4] David Burstein,[6] Hongjun Su,[2] Yong-ik Byun,[7] Licai Deng,[2,4] Zugan Deng,[4,8] Xiaohui Fan,[2,9] Zhaoji Jiang,[2,4] Yong Li,[6] Weipeng Lin,[2,4] Feng Ma,[3] Wei-hsin Sun,[7] Beverley Wills,[3] Rogier A. Windhorst,[6] Hong Wu,[2,4] Xiaoyang Xia,[4,10] Wen Xu,[2,6] Suijian Xue,[2,4] Haojing Yan,[2,6] Xu Zhou,[2,4] Jin Zhu,[2,4] and Zhenlong Zou[2,4]
Received 1998 April 29; accepted 1998 June 30; published 1998 July 27

ABSTRACT

The edge-on, nearby spiral galaxy NGC 5907 has long been used as the prototype of a "noninteracting" warped galaxy. We report here the discovery of two interactions with companion dwarf galaxies that substantially change this picture. First, a faint ring structure is discovered around this galaxy that is likely due to the tidal disruption of a companion dwarf spheroidal galaxy. The ring is elliptical in shape with the center of NGC 5907 close to one of the ring's foci. This suggests that the ring material is in orbit around NGC 5907. No gaseous component to the ring has been detected either with deep Hα images or in Very Large Array H I 21 cm line maps. The visible material in the ring has an integrated luminosity $\leq 10^8\ L_\odot$, and its brightest part has a color $R - I \sim 0.9$. All of these properties are consistent with the ring being a tidally disrupted dwarf spheroidal galaxy. Second, we find that NGC 5907 has a dwarf companion galaxy, PGC 54419, which is projected to be only 36.9 kpc from the center of NGC 5907, close in radial velocity ($\Delta V = 45$ km s^{-1}) to the giant spiral galaxy. This dwarf is seen at the tip of the H I warp and in the direction of the warp. Hence, NGC 5907 can no longer be considered noninteracting but is obviously interacting with its dwarf companions much as the Milky Way interacts with its dwarf galaxies. These results, coupled with the finding by others that dwarf galaxies tend to be found around giant galaxies, suggest that tidal interaction with companions, even if containing a mere 1% of the mass of the parent galaxy, might be sufficient to excite the warps found in the disks of many large spiral galaxies.

Subject headings: galaxies: individual (NGC 5907, PGC 054419) — galaxies: interactions — galaxies: photometry — galaxies: spiral — radio lines: galaxies

1. INTRODUCTION

NGC 5907 is an edge-on spiral galaxy that is large in angular size, with a well-known warp both in its H I gas (Sancisi 1976; see also below) and in its optical disk (Sasaki 1987; Morrison, Boroson, & Harding 1994; Zheng et al. 1998). As such, it has been a popular galaxy in which to study the vertical luminosity distribution in a spiral galaxy, not only in the optical (Morrison et al. 1994; Sackett et al. 1994; Lequeux et al. 1996; Lequeux et al. 1998; Zheng et al. 1998) but also in the infrared (Rudy et al. 1997). Much of the recent interest on NGC 5907 was stimulated by the announcement by Sackett et al. of the detection of a faint luminous halo around it, which appears to have a luminosity radial profile that traces that of the dark halo mass.

We present here deep optical images and new VLA H I maps of NGC 5907 that are used to reassess the origin of the warp in this galaxy. In a separate paper (Zheng et al. 1998), we will use these same data to study the halo of NGC 5907 in detail.

2. OBSERVATIONS

Optical observations of NGC 5907 were made as part of the Beijing-Arizona-Taiwan-Connecticut (BATC) Color Survey of the Sky (see Fan et al. 1996). This survey uses the Beijing Astronomical Observatory (BAO) 0.6/0.9 m Schmidt telescope equipped with a 2048 × 2048 Ford CCD and a custom-designed set of 15 intermediate-band filters to do spectrophotometry for specific 1 deg^2 regions of the northern sky. NGC 5907 is in the center of one of these regions and, given the great interest in its low surface brightness properties, we obtained long integrations of it in two BATC filters: central wavelength 6660 Å, bandwidth 480 Å (m_{6660}) and central wavelength 8020 Å, bandwidth 260 Å (m_{8020}).

The CCD subtends $58' \times 58'$ ($1''.71$ pixel^{-1}) in the focal plane of the BAO Schmidt. Out of 43 hr of actual observation of NGC 5907 at 6660 Å, we selected the 84 best images for analysis, with a total exposure time of 26.17 hr (Zheng et al. 1998). The telescope was centered at slightly different positions for these images for greater reliability of flat-fielding. Figure 1 shows the inner part of the combined BATC m_{6660} image with low surface brightness features emphasized. We also obtained 21 hr of integration with the 8020 Å filter, of which the best 16.7 hr were used. By directly comparing with standard broadband photometry of NGC 5907 (Morrison et al. 1994; Rudy et al. 1997), we obtain the transformation between our two bands and R and I bands (Zheng et al. 1998). Within an error of 0.5 mag arcsec^{-2}, our limiting magnitudes correspond to 28.6 and 26.9 mag arcsec^{-2} in R and I, respectively.

As is evident from Figure 1, a luminous ring encompasses

[1] Partially based on observations taken with the Very Large Array of the National Radio Astronomy Observatory is a facility of the National Science Foundation operated by a cooperative agreement with Associated Universities, Inc.

[2] Beijing Astronomical Observatory, Chinese Academy of Sciences, Beijing 100080, China.

[3] Department of Astronomy, University of Texas at Austin, Austin, TX 78712; shang@astro.as.utexas.edu.

[4] Beijing Astrophysics Center, Beijing, 100871, China.

[5] Departamento de Astronomía, Universidad de Guanajuato, Apartado Postal 144, Guanajuato, Gto. 36000, Mexico.

[6] Department of Physics and Astronomy, Box 871504, Arizona State University, Tempe, AZ 85287-1504.

[7] Institute of Astronomy, National Central University, Chung-Li, Taiwan.

[8] Graduate School, Chinese Academy of Sciences, Beijing 100080, China.

[9] Princeton University Observatory, Princeton, New Jersey, 08544.

[10] Department of Physics, Tianjin Normal University, China.

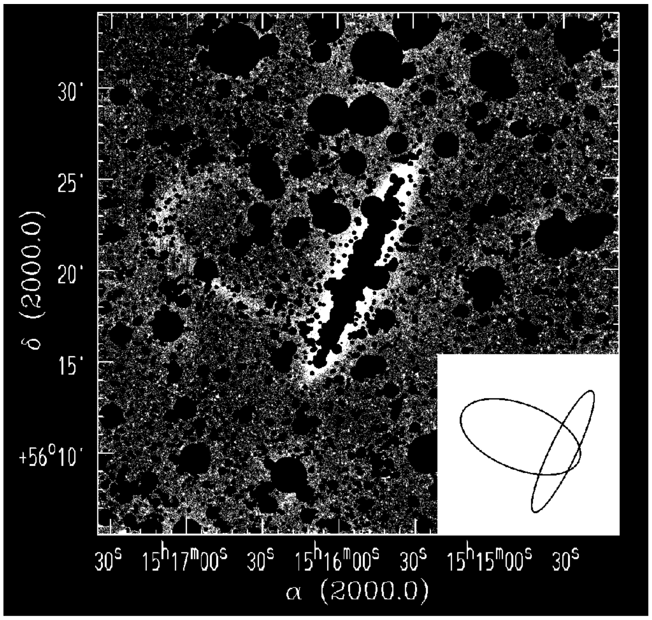

FIG. 1.—Combined 26.17 hr BAO Schmidt image of a $28' \times 28'$ subfield of our $58' \times 58'$ image, centered around NGC 5907 and taken through the 6660 Å BATC filter. All foreground stars, other galaxies (including PGC 54419), and the dust lane of NGC 5907 have been blanked. This permits displaying a range of gray levels to enhance the faintest surface brightness features in this galaxy. The inset diagram shows the shape of the ring and its relative orientation with respect to NGC 5907.

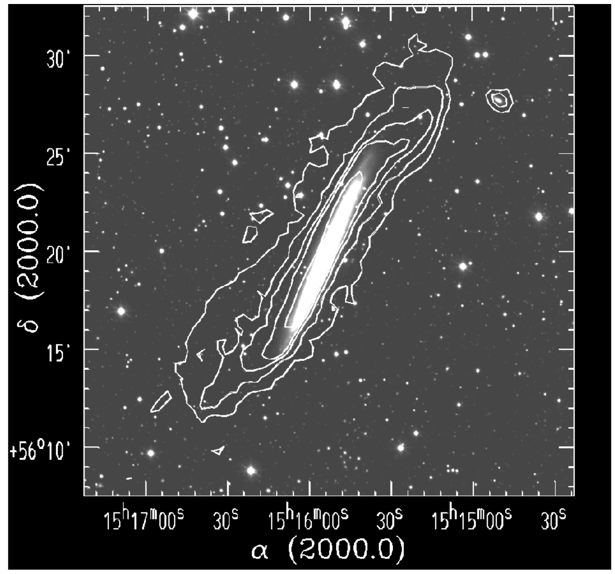

FIG. 2.—Integrated intensity map of 21 cm emission as derived from our 6 hr VLA observation, superposed on our m_{6660} image, of size $25' \times 25'$. The 21 cm contours are 0.69 (3 σ), 4.0, 12.5, 22.5, and 75 mJy beam^{-1} (1 mJy beam^{-1} = 1.85 K). The beam width is 18″. Note the discovery of H I at a similar velocity as NGC 5907 in the dwarf galaxy PGC 54419, which is off to the upper right.

this galaxy. The part of this ring closest to NGC 5907 can be seen faintly in Figure 3 of Morrison et al. (1994). In separate papers (Zheng et al. 1998; Chen et al. 1998), we detail the data taking and data reduction processes that permit us to reliably investigate low surface brightness features on our images. For this Letter, we present Figure 1 as evidence that we can reliably flat-field large portions of our images to very faint surface brightnesses.

We have also used the McDonald Observatory 0.76 m telescope (field of view $46' \times 46'$ with a 2048×2048 CCD) to obtain broadband R (4.5 hr) and 30 Å wide Hα (7.5 hr) and [O III] (2.5 hr) images of NGC 5907. The narrowband filters are of sufficient width to cover gas emission from zero velocity to well past the 667 km s^{-1} heliocentric recession velocity of NGC 5907. The ring clearly appears in the 0.76 m R images (ruling out ghost images on Schmidt plates as a possible source) but does not appear in either narrowband image (the exposures of which are too short to see the ring in just the faint continuum), confirming previous Hα observations (Rand 1996).

In order to understand the distribution of neutral hydrogen gas around NGC 5907, 21 cm H I line observations were obtained with the VLA in its modified C array (one antenna each from the middle of the east and west arm having been moved inward to improve coverage of the inner portion of the u-v plane). We employed spectral line mode 4, in which the two independently tunable passbands are used to cover a total velocity range of around 1000 km s^{-1}, centered on 667 km s^{-1} and with a velocity resolution of 20 km s^{-1}. To optimize sensitivity, both right- and left-hand polarized emission are recorded.

At 21 cm, the field of view of the VLA is about 32′, which is large enough to include the area of interest. Since our aim was to go as deep as possible, naturally weighted maps were made, leading to a synthesized beam of 18″, which is sufficient to resolve the ring. The total integration time of 6 hr results in a 1 σ noise level of 0.23 mJy beam^{-1}. This translates to a column density of 9×10^{19} atoms cm^{-2} assuming a 3 σ detection in two adjacent channels. The resulting H I map, superposed on our optical image of NGC 5907, is shown in Figure 2. The observations confirm the impressive warp reported earlier by Sancisi (1976). On the other hand, within the quoted sensitivity limits, no H I was found to coincide with the optical ring.

3. THE RING

The possible physical interpretations of this ring are either Galactic in origin—"cirrus," planetary nebula, or supernova remnant—or physically associated with NGC 5907. Examination of the whole BATC field of view (only one-fourth of which is shown in Fig. 1) shows no other evidence of ringlike structures near NGC 5907. In addition, the Burstein-Heiles (Burstein & Heiles 1984) predicted reddening for this galaxy is only $E(B-V) = 0.003$. These two facts make it unlikely that this ring is an artifact due to Galactic cirrus. If the ring has a Galactic origin, its ionized gas should easily have been detected on our narrowband filter images. In addition, from our images we measure the $m_{6660} - m_{8020}$ color to be 0.7 ± 0.3 mag arcsec^{-2}, of the brightest part of the ring (26.8 ± 0.1 m_{6660} arcsec^{-2}). This corresponds to an $R-I$ color of 0.9 ± 0.4 based on our transformation to broadband photometry—certainly not the color of a planetary nebula. These observations, together with the fact that the field is at high Galactic latitude ($b = +51°$), make it highly unlikely that this ring could be a Galactic supernova remnant or a planetary nebula. While we can not completely rule out the possibility that this is a planetary nebula, it would have to be relatively close (within 1 kpc) and very old and cold, with little ionized gas.

Alternatively, the ring is physically associated with NGC 5907. To test this hypothesis, we derived the luminosity distribution along the ring and fitted it with an ellipse (Fig. 3).

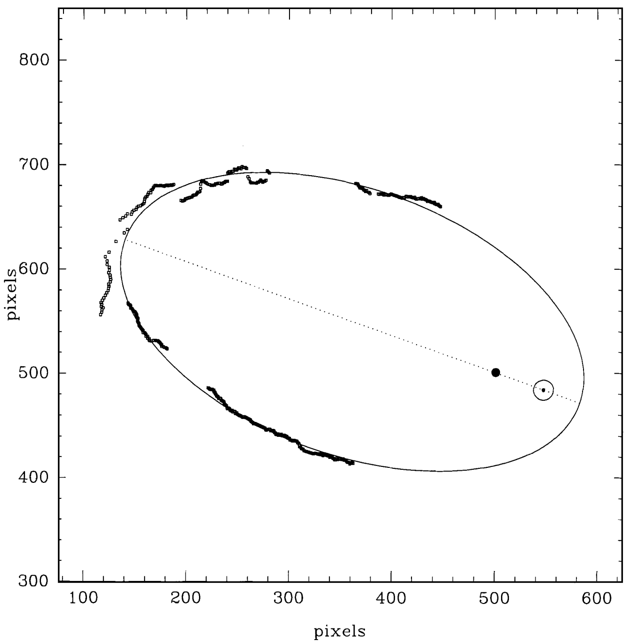

FIG. 3.—Peak brightness distribution along the ring and the fitted ellipse. Only the clear part of the ring is measured. The major axis is 13′.4; the minor axis is 7′.3 with eccentricity of 0.84. The small dot is the center of NGC 5907, while the open circle shows the focus of the ring nearest the galaxy nucleus. The radius of this circle (10 pixels) indicates the position error of the focus location. Also shown is the major axis of the ring.

We find that it is almost perfectly elliptical in shape. Within the errors, the center of the galaxy falls on the ring's major axis and is close to one of its foci, as should be the case if the material in the ring is in orbit around NGC 5907. The separation of 1′.4 between the focus and the center of NGC 5907 implies an orbit inclination of 45°, intrinsic ring dimensions of 13′.4 × 10′.3, and an eccentricity of 0.63.

The major axis size is the same as the optical diameter of NGC 5907 itself: 43 kpc at an assumed distance of 11 Mpc (using $H_0 = 75$ km s^{-1} Mpc^{-1}). Thus, based both on the lack of a plausible alternative and a plausible orbital interpretation of the ring, our conclusion is that the ring is physically associated with NGC 5907.

How bright is the ring? Fan et al. (1996) showed that we can flat-field BATC images to better than 1% accuracy (see also Zheng et al. 1998) and photometrically calibrate them to 1%–2% absolute accuracy using flux standard stars (Oke & Gunn 1983). Our images yield average sky brightnesses of 21.25 mag arcsec^{-2} at 6660 Å and 19.91 mag arcsec^{-2} at 8020 Å, respectively (on the A_B standard system of Oke & Gunn 1983). We get $m_{6660} \geq 14.7$ for the ring by taking the average surface brightness for the part of the ring we can see and assuming a complete ring of similar surface brightness.

In contrast, by replacing all foreground stars with the mean value of the surrounding background, we find that NGC 5907 itself has $m_{6660} \approx 9.9$ to a surface brightness of 27 m_{6660} arcsec^{-2}. From our VLA observations, we obtain a rotation velocity of 205 km s^{-1} and an outer H I radius of 7′.5 (25 kpc), giving a dynamical mass of 1.9×10^{11} $M_\odot$.

Based on these measurements, the luminosity of the ring is ≤1.2% that of the galaxy, or an absolute 6660 Å luminosity of ≤10^8 $L_\odot$. While it is evident that the ring is not of uniform surface brightness, this upper limit is comparable to the luminosity estimated for the Sagittarius dwarf galaxy, which was recently found to be in the process of tidal disruption by our own Galaxy (Ibata, Gilmore, & Irwin 1994.) The $R - I$ color of ~0.9 of the brightest part of the ring suggests that the optical emission is mostly from late-type stars.

The lack of detection of gas in the ring, either in the VLA 21 cm map or the Hα and [O III] images, suggests that gas is a minor constituent of this ring. For example, suppose the pre–tidally distorted dwarf galaxy originally had an equal amount of gas associated with it as stars (a reasonable assumption for low-mass, dIrr galaxies), or ~10^8 $M_\odot$. If we distribute this gas evenly along the ring, we would expect a column density of 4×10^{19} atoms cm^{-2}, which is close to our detection limit. Only modest clumping would be sufficient for us to detect this gas, which we do not see (Fig. 2). We thus conclude that the ring consists mostly of stars, in agreement with its measured $R - I$ color.

4. PGC 54419 AND THE WARP

Our VLA map clearly shows the well-known warped H I disk of NGC 5907 (e.g., Sancisi 1976) extending far beyond the optical disk. Because of the absence of any nearby galaxy candidate, NGC 5907 has long been considered a prime example (Sancisi 1976) of a "noninteracting" galaxy with an H I warp. However, our VLA map reveals that the object PGC 54419, which was once considered to be a background object, has a radial velocity of 712.0 ± 1.5 km s^{-1}, or only 45 km s^{-1} from that of the main galaxy. It therefore is a dwarf companion at a projected distance of 36.9 kpc (~11′.5) from the nucleus of NGC 5907. It is located near the northern tip and in the direction of the warp, at some 3′.7 (12 kpc) in projection to the west. PGC 54419 is likely closer to NGC 5907 than the Magellanic Clouds are to the Milky Way.

We obtain $m_{6660} = 15.34 \pm 0.02$ and $m_{8020} = 15.33 \pm 0.02$ for PGC 54419, with $m_{6660} - m_{8020} = 0.01 \pm 0.03$ ($R - I \sim 0.2$). From Fan et al. (1996), we estimate its V magnitude to be essentially the same as its m_{6660} magnitude, or $V = 15.34$. The angular size of PGC 54419 is 54″.6 × 31″.4 (2.9 × 1.7 kpc), yielding an inclination of 56°.6 (based on an intrinsic axial ratio of 0.2). From the VLA data, we observe an H I profile with full width at 20% maximum of 88 km s^{-1}, giving an inclination-corrected rotation velocity of 53 km s^{-1}. From this, we measure the mass of PGC 54419 to be 9.5×10^8 $M_\odot$ (0.5% the mass of NGC 5907) and its mass-to-light ratio to be 12 in solar units. From the VLA H I profile, we measure an H I mass of 3.6×10^7 $M_\odot$ for this galaxy. In all of its measured characteristics, PGC 54419 is a dwarf irregular galaxy (Roberts & Haynes 1994) and is likely misclassified as a spiral galaxy (see Paturel 1989).

It is of interest to understand why PGC 54419 was not previously detected in H I by Sancisi (1976). The object measures, in the channel map at 715 km s^{-1} in which it is most clearly seen, about 30″ × 12″ (at a position angle of ~65°) and has an integrated flux density of 14 ± 2 mJy. Once smoothed to the resolution obtained by Sancisi (51″ × 61″), the source has become unresolved and its flux density corresponds to 2.6 K, or less than 4 σ in Sancisi's maps. The signal in neighboring channels falls well below 3 σ, which explains why it was not detected in the Westerbork data.

5. DISCUSSION

We propose that the ring around NGC 5907 was once a dwarf spheroidal galaxy in orbit around NGC 5907 that is now tidally disrupted by its interaction with the larger galaxy. A nearby (at 36.9 kpc projected distance) dwarf irregular galaxy is suggestively situated right at the end of the more prominent warp in NGC 5907 (Fig. 2). At the very least, NGC 5907 is no longer a noninteracting galaxy with an H I warp.

Low surface brightness, ringlike structures may be common around galaxies, since few nearby galaxies have been probed as deeply as NGC 5907. Even our own Galaxy is tidally interacting with its entourage of dwarf galaxies (e.g., the Sagittarius dwarf; Magellanic stream) and is a likely candidate for such a ringlike feature in the future (Johnston, Spergel, & Hernquist 1995). Indeed, models by Johnston et al. (1995) show that such a ring could exist from the tidal disruption of a dwarf galaxy in much the form we see it around NGC 5907. A dwarf spheroidal galaxy would have low velocity dispersion (Bender, Burstein, & Faber 1992), so its tidal debris would tend to produce a coherent stream. The stream would tend to bunch up at apogalacticon, which is near where we see the highest surface brightness in the NGC 5907 ring. The models of Johnston et al. indicate that such rings can persist for ∼2 dynamical timescales, or $\sim 1 \times 10^9$ yr in the case of NGC 5907 (rotation velocity of 205 km s^{-1} from our H I data).

The situation is not as clear with regard to how the ring and PGC 54419 are related to the H I warp in NGC 5907. The ring and dwarf galaxy combined have ∼1% of the luminosity of NGC 5907 and likely a similar percentage of its mass. On the one hand, Weinberg (1995) points out that, in the case of the LMC and the Galaxy, a dynamically active halo acts to amplify the tidal warping effect of a small galaxy on the disk of a much larger galaxy through distortion of the halo of the larger parent galaxy. On the other hand, the LMC is 10% of the mass of the Milky Way, while the ring and dwarf are much smaller compared to NGC 5907. It remains to be seen whether realistic models of tidal interactions of outer H I disks with small companion dwarf galaxies can produce the warps, both H I and optical seen in NGC 5907.

Related to this issue is that detailed investigation of the H I map shows that the vertical distribution of H I is not symmetric on both sides near the central region of the galaxy. On the side of the ring there are weak H I features just above 3 σ level, as may result from tidal interaction between the ring material and the disk. Deeper VLA maps of this galaxy will be needed to confirm this feature.

Finally, it is well known that dwarf galaxies tend to group around giant spiral galaxies. Such is certainly the case for the Milky Way and M31 in the Local Group (e.g., Grebel 1997). The study of Zaritsky et al. (1997) shows the same to be true around most giant spiral galaxies, even "isolated" giant spirals. While it would be very hard to show that a galaxy did *not* have dwarf companions, given their low surface brightnesses, it is also equally hard to show that all galaxies have them. Only by taking a deep look at the environments around isolated spiral galaxies with warped disks can this issue be resolved.

We thank McDonald Observatory for supporting part of the observations and data reductions, David Spergel for a helpful conversation, the VLA personnel for efficient service, and the anonymous referee for helpful comments. This research is supported in part by the Chinese National Natural Science Foundation (CNNSF) and by the US National Science Foundation (NSF grant INT-93-01805).

REFERENCES

Bender, R., Burstein, D., & Faber, S. M. 1992, ApJ, 399, 462
Burstein, D., & Heiles, C. 1984, ApJ, 54, 33
Chen, J., et al. 1998, AJ, submitted
Fan, X., et al. 1996, AJ, 112, 628
Grebel, E. K. 1997, Rev. Mod. Astron., 10, 29
Ibata, R. A., Gilmore, G., & Irwin, M. J. 1994, Nature, 370, 194
Johnston, K. V., Spergel, D. N., & Hernquist, L. 1995, ApJ, 451, 598
Lequeux, J., Combes, F., Dantel-Fort, M., Cuillandre, J.-C., Fort, B., & Mellier, Y. 1998, A&A, 334, L9
Lequeux, J., Fort, B., Dantel-Fort, M., Cuillandre, J.-C., & Mellier, Y. 1996, A&A, 321, L1
Morrison, H., Boroson, T., & Harding, P. 1994, AJ, 108, 1191
Oke, J. B., & Gunn, J. E. 1983, ApJ, 266, 713
Paturel, G., Fouqué, P., Bottinelli, L., & Gouguenheim, L. 1989, Catalogue of Principal Galaxies (Lyon: Observatoire de Lyon)
Rand, R. 1996, ApJ, 462, 712
Roberts, M. S., & Haynes, M. P. 1994, ARA&A, 32, 115
Rudy, R. J., Woodward, C. E., Hodge, T., Fairfield, S. W., & Harker, D. E. 1997, Nature, 387, 159
Sackett, P. D., Morrison, H. L., Harding P., & Boroson, T. A. 1994, Nature, 370, 441
Sancisi, R. 1976, A&A, 53, 159
Sasaki, T. 1987, PASJ, 39, 849
Weinberg, M. 1995, ApJ, 455, L31
Zaritsky, D., Smith, R., Frenk, C., & White, S. D. M. 1997, ApJ, 478, 39
Zheng, Z., et al. 1998, in preparation