Small Galaxy Groups
ASP Conference Series, Vol. 209, 2000
M. Valtonen and C. Flynn, eds.

Deep Optical Imaging of the Compact Group "Seyfert's Sextet"

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Abstract. The compact group of galaxies "Seyfert's Sextet" shows irregularly shaped soft X-ray morphology. In order to understand its origin, we have obtained a deep optical ($VR + I$) image of the group. Our image shows that a faint envelope surrounds the member galaxies. We find that optical and soft X-ray images are significantly similar in morphology. This similarity provides direct morphological evidence that the dark matter in Seyfert's Sextet was originally associated with the individual galaxies and is now spreading out around the group.

1. Introduction

Where predominantly is the dark matter in the universe? Since this question is intimately related both to the history of galaxies and to cosmology, many investigations have been devoted to understanding this issue (Ostriker, Peebles, & Yahil 1974; Einasto, Kaasik, & Saar 1974; Faber & Gallagher 1979; Davis et al. 1980; Trimble 1987; Zaritsky 1992; Zaritsky et al. 1997; Dell' Antonio et al. 1994; Bahcall, Lubin & Dorman 1995; Zabludoff & Mulchaey 1998). Earlier investigations suggested that larger-scale systems such as clusters of galaxies tend to have higher mass contribution from the dark matter than smaller ones. On the other hand, Bahcall et al. (1995) suggested that most of the dark matter may reside in very large halos around galaxies. Thus the major location of the dark matter appears still in question.

Since groups of galaxies are intermediate between isolated galaxies and rich clusters of galaxies, it is important to investigate their dynamical properties in detail. Recently, the X-ray satellite ROSAT has been used to investigate the dark matter content in a large number of compact groups of galaxies (Ponman & Bertram 1993; Ebeling, Voges, & Böhringer 1994; Pildis, Bregman, & Evrard 1995; Saracco & Ciliegi 1995; Ponman et al. 1996; Mulchaey & Zabludoff 1998). The majority of groups of galaxies detected by ROSAT show round-shaped morphologies in soft X-rays. On the other hand, some groups such as Seyfert's Sextet (hereafter SS), show irregular-shaped soft X-ray morphologies (Pildis et al. 1995). In this paper, we try to understand the origin of the irregular-shaped soft X-ray morphology of SS.

SS is one of the most famous and the densest compact among groups of galaxies. This group is also listed as one of Hickson's Compact Groups of Galaxies, HCG 79 (Hickson 1982, 1993). SS consists of four redshift-accordant galaxies (HCG79a, HCG79b, HCG79c, and HCG79d) (Seyfert 1948a, 1948b) and a

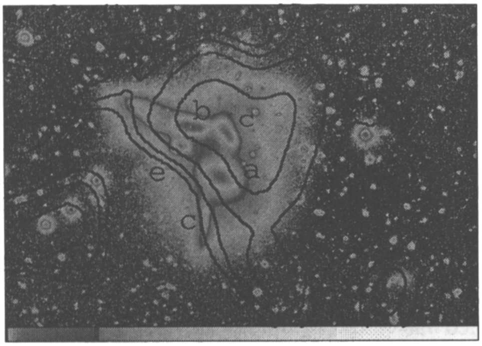

Figure 1. $VR + I$ image of SS (gray scale) and X-ray intensity map (contours).

redshift-discordant galaxy (HCG 79e). We use a distance to SS, $44h^{-1}$ Mpc and a Hubble constant, $H_0 = 100\ h$ km s^{-1} Mpc^{-1}.

2. Observations

Optical $VR-$ and $I-$band deep imaging of SS was obtained with the 8k mosaic CCD camera (8192×8192 pixels) attached to the University of Hawaii 88-inche telescope at Mauna Kea Observatory. Two-pixel binning was made and thus the spatial resolution was 0.26 arcsec per element. The total integration time was 10560 seconds (VR) and 11520 seconds (I). The seeing size was 0.8 arcsec during the observation.

In order to investigate the nuclear activity of the member galaxies of SS, we have performed optical spectroscopy. Optical spectra were obtained with the New Cassegrain spectrograph attached to the 188 cm telescope at the Okayama Astrophysical Observatory. A blazed grating of 600 grooves mm^{-1} was used at 7,500 Å. The spectral coverage was 6,200 Å- 6,900 Åwith a spectral resolution of 2.4 Å at 6,500 Å. The integration time was 1800 seconds for each galaxy. The spatial resolution was 1.75 arcsec pixel^{-1} and the slit width was 1.8 arcsec. The seeing size was 2 arcsec during the observations.

3. Results

The $VR + I$ image is shown in Figure 1 (gray scale). The faintest surface brightness detected in our image is $\mu_{\rm optical}$(AB) $\simeq$ 27 mag arcsec^{-2}. We can see the faint optical envelope surrounding SS in the VR image. This overall morphology is consistent with that obtained previously (Sulentic & Lorre 1983).

Nuclear spectra of member galaxies are shown in Figure 2. Our results of spectroscopic observation show that HCG 79a and 79b are LINERs (=low

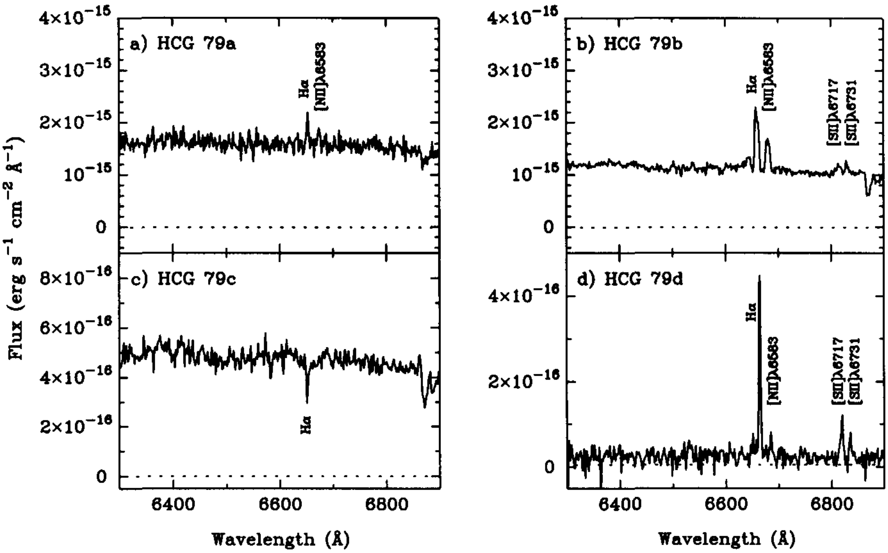

Figure 2. Optical spectra of a) HCG 79a, b) HCG 79b, c) HCG 79c, and d) HCG 79d.

ionization nuclear emission-line regions: Heckman 1980), while 79d is a weak H II galaxy. HCG 79c shows no emission-line activity.

4. Discussion

4.1. The Origin of Soft X-ray Emission

The soft X-ray luminosity of SS is $L_X^{obs} \simeq 1.3 \times 10^{41} h^{-2}$ ergs s^{-1} assuming hot gas temperature 1 keV and abundance 0.3 solar (Ponman et al. 1996). It is possible that a part of the hot gas may be associated with individual member galaxies. Here we examine whether or not the soft X-ray emission of SS arises really from hot gas because supernova remnants, low- and high-mass X-ray binaries, and/or active galactic nuclei contribute to the soft X-ray emission to some extent if they are present in the member galaxies.

We estimate expected soft X-ray luminosities of discrete sources such as X-ray binaries in the individual galaxies and possible contribution of active galactic nuclei or starburst activity in the member galaxies. Soft X-ray luminosities from discrete sources in the member galaxies can be estimated using the following empirical L_X - L_B relationships for galaxies where L_B is the absolute blue luminosity. $\log L_X = (2.47 \pm 1.01) \times \log L_B - (68.36 \pm 44.08)$, for early-type galaxies (Brown & Bregman 1998), and $\log L_X = (1.21 \pm 0.03) \times \log L_B - (13.29 \pm 1.39)$. for late-type ones (Read, Ponman, & Strickland 1997; Vogler, Pietish, & Kahabka 1996). The optical B luminosities of member galaxies L_B were estimated using apparent blue magnitudes (Hickson 1993). Although HCG 79e is the redshift-discordant galaxy, this galaxy also contributes to the observed soft X-ray luminosity of SS because it lies in a line of sight toward the group. For LINERs, Koratkar et al. (1995) obtained an average soft X-ray to Hα luminosity ratio, $\log L_X/L_{\mathrm{H}\alpha} \simeq 0.97 \pm 0.51$. H$\alpha$ luminosities were obtained in our spectroscopic observations. For a starburst galaxy, we obtained an average soft X-ray to optical B luminosity ratio from Read et al. (1997), $\log L_X/L_B \simeq -3.87 \pm 0.19$. Finally, an expected total soft X-ray luminosity coming from individual soft X-ray sources in the five galaxies $L_{\mathrm{X,gal}}^{\mathrm{exp}}$ is $4.4 \times 10^{39} h^{-2}$ ergs s^{-1}. A total soft X-ray luminosity from two LINERs $L_{\mathrm{X,AGN}}^{\mathrm{exp}}$ is $2.7 \times 10^{40} h^{-2}$ ergs s^{-1}. X-ray luminosity from starburst activity $L_{\mathrm{X,SB}}^{\mathrm{exp}}$ is $7.1 \times 10^{38} h^{-2}$ ergs s^{-1}. Since this accounts for only a quarter of the observed soft X-ray luminosity, it is suggested that the most soft X-ray emission of SS comes from the hot gas rather than from individual X-ray sources.

Now a question arises; "With which is the hot gas associated, the individual galaxies or the global group potential ?" We compare our very deep optical image (gray scale) with the soft X-ray image (contours) taken by Pildis et al. (1995) in Figure 1. It is seen that the soft X-ray morphology is quite similar to the optical one. The optical faint envelope should be attributed to stars liberated from the member galaxies through historical and on-going tidal interactions. Therefore, the morphological similarity between the optical and soft X-ray images implies that the dark matter in SS was originally associated with the individual galaxies and then has been liberated tidally together with stars.

4.2. The Mass of the Dark Matter in Seyfert's Sextet

It is impossible to estimate the mass of hot gas because of the lack of information on the temperature of the gas (Pildis et al. 1995). In order to estimate the mass of the dark matter, we estimate both a dynamical mass of SS (most of which is considered to be attributed to the dark matter) and a total mass of the individual member galaxies based on their optical B luminosities.

First, we estimate a dynamical mass of SS. Heisler, Tremaine & Bahcall (1985) have proposed four mass estimators for small-member galaxy associations such as compact groups of galaxies; 1) the virial mass estimator, 2) the projected mass estimator, 3) the average mass estimator, and 4) the median mass estimator. In order to avoid accidental errors in each mass estimator, we estimate the total mass of SS averaging masses derived from these four estimators; $M_{\mathrm{tot}} \simeq 3.6 \times 10^{11} h^{-1} M_\odot$. Second, we estimate the mass of dark matter that could be associated with the member galaxies of SS, M_{gal}. Mass-to-luminosity ratio for each Hubble type are as follows: 13.7 ± 0.3 for early-type galaxies (Bacon, Monnet, & Simien 1985), 9.1 ± 4.0 for Sdm galaxies. We estimate a typical mass-to-luminosity ratio for Sdm galaxies by averaging of that of Sc galaxies, 5.2 $\pm$ 0.4 (Rubin et al. 1985) and that of irregular galaxies, 12.9 ± 7.5 (Lo, Sargent & Young 1993). Therefore, the B luminosity derived above can be regarded as the stellar B luminoisty. We thus obtain a total (i.e., stars, gas, and the dark matter) mass of the individual galaxies of SS, $M_{\mathrm{gal}} \simeq 2.7 \times 10^{11} h^{-1} M_\odot$; note that M_{gal} does not contain the mass of dark matter in intragroup space. Since this mass shares 73 % of the dynamical mass of SS, the majority of the dark matter is associated with the member galaxies.

4.3. Dynamical Evolution of Seyfert's Sextet

The irregular-shaped soft X-ray morphology of SS suggests that the dark matter in SS has not completely relaxed dynamically yet. This appears consistent with the observation that the member galaxies in SS show morphological and kinematical evidence for violent interactions. It is thus strongly suggested that SS is a dynamically-young, compact group of galaxies which are going to merge. It has been numerically shown that a merging time scale of a compact group with galaxies each of which has a dark halo is much shorter (i.e., $\sim 10^9$ yr) than the Hubble time (Athanassoula, Makino, & Bosma 1998). Therefore, it is expected that SS will merge into one unit within a time scale less than 10^9 years and finally evolve into an elliptical galaxy with a large, virialized halo.

Table 1. Properties of Seyfert's Sextet.

R	$8\ h^{-1}$ kpc
$L_{\rm X}^{\rm obs}$	$1.3 \times 10^{41} h^{-2}\ L_\odot$
$L_{\rm X,gal}^{\rm exp}$	$4.4 \times 10^{39} h^{-2}\ L_\odot$
$L_{\rm X,AGN}^{\rm exp}$	$2.7 \times 10^{40} h^{-2}\ L_\odot$
$L_{\rm X,SB}^{\rm exp}$	$7.1 \times 10^{38} h^{-2}\ L_\odot$
$M_{\rm tot}$	$3.6 \times 10^{11} h^{-1}\ M_\odot$
$M_{\rm gal}$	$2.7 \times 10^{11} h^{-1}\ M_\odot$
L_B	$2.0 \times 10^{10} h^{-2}\ L_\odot$
$M_{\rm tot}/L_B$	$18 h M_\odot / L_\odot$

Such a fossil group of galaxies has been reported; a soft X-ray source turns out to be an elliptical galaxy with a large-scale X-ray halo (Ponman et al. 1994; Matsushita et al. 1998; Mulchaey & Zabludoff 1999). We investigate a relationship between the mass-to-light ratio ($M_{\rm tot}/L_B$ where L_B is the absolute B luminosity) and the radius (R) of SS and compare it with those of the above candidates of fossil groups and typical elliptical galaxies studied by Bahcall et al. (1995). Summing the blue luminosities of the four member galaxies, we obtain a total blue luminosity of SS, $L_B \simeq 2.0 \times 10^{10} h^{-2} L_\odot$. We thus obtain a mass-to-light ratio of SS, $M/L_B \simeq 18 h M_\odot/L_\odot$. The linear size of SS is $R \simeq 8h^{-1}$ kpc which is the radius of circle including the center of all member galaxies. It seems worthwhile noting that the relationship between M/L_B and R for SS follows well that for elliptical galaxies (Bahcall et al. 1995). A merger remnant of SS will evolve to an ordinary elliptical galaxy. We summarize the photometrical and dynamical properties of SS in Table 1.

Acknowledgments. We would like to thank the staff members of the Mauna Kea Observatory, the University of Hawaii and the Okayama Astrophysical Observatory for their kind assistance of our observations. We thank Yoshiaki Taniguchi, Takashi Murayama, and Makoto Hattori for useful discussion. We also thank Masashi Shimada, D. B. Sanders, Yasunori Sato, Youichi Ohyama and Tohru Nagao for their kind help during the course of this study. This work was supported in part by the Ministry of Education, Science, Sports and Culture in Japan under Grant Nos. 07055044, 10044052, and 10304013. The IAU kindly assisted with a travel grant.

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