1993ApJ...404L...9M

THE ASTROPHYSICAL JOURNAL, 404:L9–L12, 1993 February 10

DIFFUSE X-RAY EMISSION FROM THE NGC 2300 GROUP OF GALAXIES: IMPLICATIONS FOR DARK MATTER AND GALAXY EVOLUTION IN SMALL GROUPS

JOHN S. MULCHAEY[1]
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218
DAVID S. DAVIS[1] AND RICHARD F. MUSHOTZKY
NASA/Goddard Space Flight Center, Laboratory for High Energy Astrophysics, Code 666, Greenbelt, MD 20771
AND
DAVID BURSTEIN
Department of Physics and Astronomy, Arizona State University, Tempe, AZ 85287-1504
Received 1992 September 15; accepted 1992 November 19

ABSTRACT

We report the detection of a hot, diffuse intragroup medium with the *ROSAT* Position Sensitive Proportional Counter in the NGC 2300 group of galaxies. This is the first time such a gas component has been found in a small group. The gas distribution is roughly symmetric, centered within ~3′ of the elliptical NGC 2300, and extends to a radius of at least 0.2 h_{50}^{-1} Mpc. A Raymond-Smith (1977) hot plasma model provides an excellent fit to the X-ray spectrum, with a best-fit value temperature of $0.9^{+0.15}_{-0.14}$ keV and abundance $0.06^{+0.12}_{-0.05}$ solar. This temperature, combined with the assumption of gravitational confinement, leads to a total mass of the group of $3.0^{+0.4}_{-0.5} \times 10^{13}\ M_\odot$. A reasonable estimate of the baryonic mass in galaxies and diffuse gas indicates that baryons can account for ~4% of this mass. A conspiracy of errors could push this number no higher than 10%–15%. This is one of the strongest pieces of evidence that dark matter dominates small groups such as this one, and is in agreement with dynamical arguments for masses of groups of galaxies. The intragroup medium in this system has the lowest metal abundance yet found in diffuse gas in a group or cluster. While not as dense as in clusters, the intragroup medium is still capable of significantly affecting the outer parts of galaxies in this group. In particular, the spiral galaxy NGC 2276 displays asymmetries in its optical and radio morphologies suggestive of an ongoing intragroup medium–galaxy encounter. This peculiar "bowshock-shaped" morphology is shared by spiral galaxies in other nearby groups, suggesting that it can be used as an optical indicator of the presence of a diffuse intragroup medium.

Subject headings: dark matter — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: individual (NGC 2276, NGC 2300) — intergalactic medium — X-rays: galaxies

1. INTRODUCTION

X-ray observations of clusters of galaxies with the *Einstein Observatory* have firmly established the presence of hot gas in these systems (e.g., Forman & Jones 1982). X-ray emission from clusters is correlated with the cluster richness (Bahcall 1977a), and such emission has been found even in poor clusters (Kriss, Cioffi, & Canizares 1983; Canizares et al. 1986). It is therefore natural to assume that diffuse X-ray emission would also be associated with groups of galaxies. Attempts to confirm this with *Einstein* were not very successful. Detections of X-ray emission from several compact groups suggested that diffuse hot gas is present in these dense systems (Biermann, Kronberg, & Madore 1982; Biermann & Kronberg 1983; Bahcall, Harris, & Rood 1984). However, such emission was not detected within more typical groups.

In this *Letter* we report the discovery with the *ROSAT* Position Sensitive Proportional Counter (PSPC) of diffuse X-ray emission from the NGC 2300 group of galaxies (Group 92 [HG92] in Huchra & Geller 1982), the first such detection. The observations and data analysis are described in § 2. The results of this analysis are given in § 3. Section 4 discusses the X-ray and mass properties of the group, and conclusions are given in § 5.

2. OBSERVATIONS

Huchra & Geller (1982) assign three galaxies to HG92: NGC 2300, a bright elliptical; NGC 2276 (Arp 25), a peculiar Sc; and NGC 2268, an Sbc. An S0 galaxy in the PSPC field, IC 455, was too faint to be included in the analysis by Huchra & Geller, but is a group member based on its redshift (Table 1) and proximity to the other galaxies.

A 6035 s *ROSAT* PSPC observation was obtained on 1992 April 25–27, centered on the spiral galaxy NGC 2276. X-ray emission is detected from NGC 2276 and NGC 2300, but not from IC 455. NGC 2268 is not in the field of the PSPC and will not be discussed further. Optical and X-ray properties of the observed group members are summarized in Table 1. The assumed distance of 45.7 Mpc comes from the Local Group radial velocity of HG92 and an assumed value of $H_0 = 50$ km s^{-1} Mpc^{-1} (Table 1).

A search for a diffuse gas component was made, with all individual X-ray sources, including the galaxies, masked with a circle of radius 1′.5. An examination of this image revealed a large region of diffuse emission centered near NGC 2300 (which was *not* in the center of the PSPC image). Figure 1 (Plate L1) shows a contour map of the diffuse X-ray emission overlaid on an optical image of the field. A radial surface brightness profile of the diffuse emission was derived, assuming azimuthal symmetry and correcting for vignetting effects. The surface brightness is not well described by an isothermal β

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[1] Also Department of Astronomy, University of Maryland.

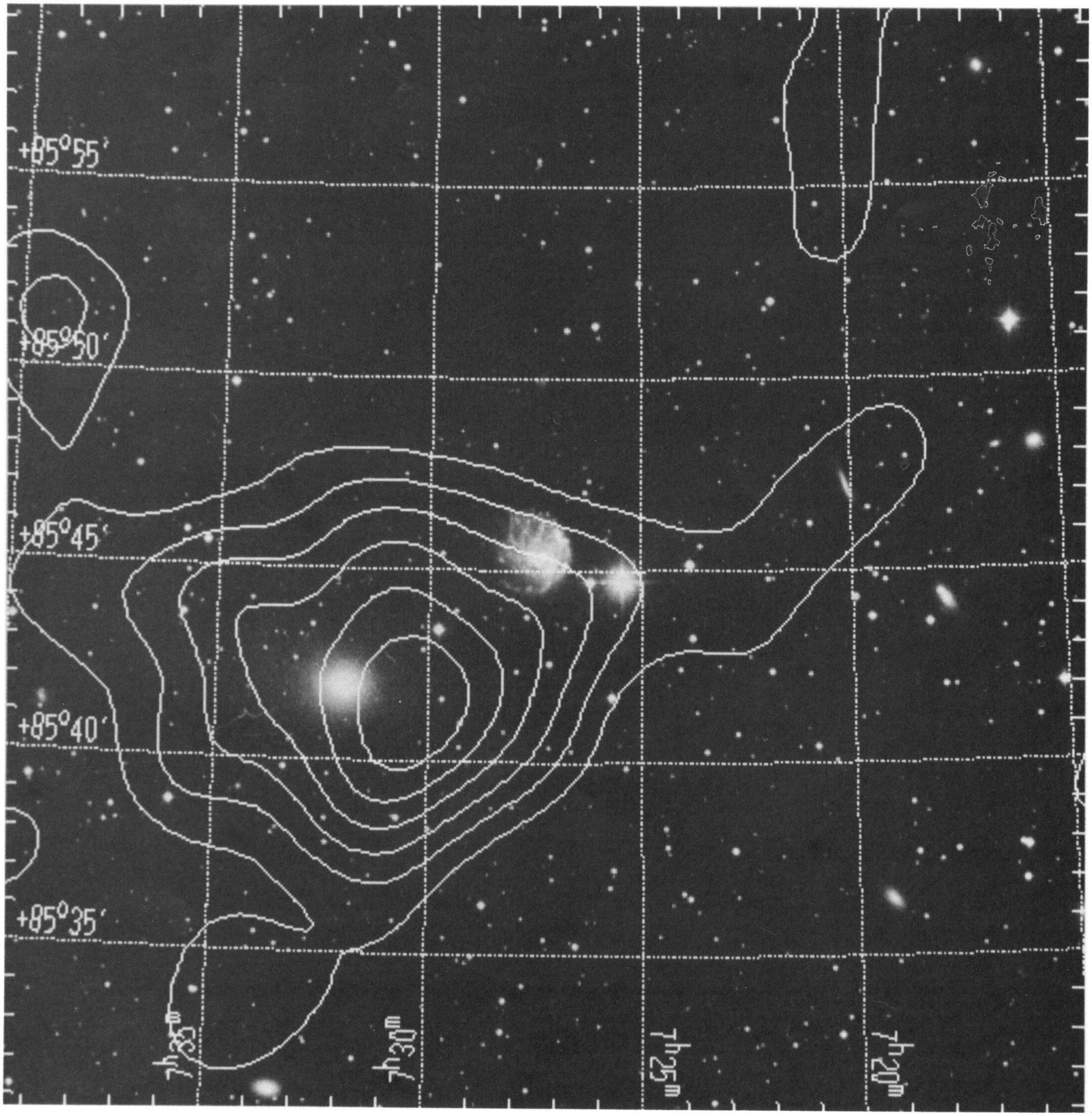

FIG. 1.—Contour map of the diffuse X-ray emission in the NGC 2300 group of galaxies (HG92), smoothed with a 2′ Gaussian, overlaid on a copy of the Palomar Sky Survey reproduced to the same scale. All X-ray emission from identifiable individual sources has been removed. The contour levels begin at 1.03×10^{-3} counts arcmin^{-2} s^{-1}, which corresponds to a level 3 σ above the background determined from the outer portions of the field. Each level is an increment of 7.95×10^{-5} counts arcmin^{-2} s^{-1} (1 σ) above the previous level.

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TABLE 1

GROUP PROPERTIES AND SPECTRAL FITS TO A RAYMOND-SMITH MODEL

	GROUP PROPERTIES				DERIVED X-RAY PARAMETERS							X-RAY PREDICTIONS		
OBJECT (1)	Type (2)	V_{Hel} (3)	D_{25} (4)	B_T (5)	Counts (6)	N_{H} (7)	kT (8)	Abundance (9)	Flux (10)	χ^2/dof (11)	L_x (12)	$L_x:\sigma$ (13)	$kT:\sigma$ (14)	$kT:L_x$ (15)
NGC 2276	Sc	2372	2.82	11.75	85	$3.3^{+29.7}_{-2.3}$	$1.12^{+0.85}_{-0.30}$	1.0	1.83	0.7/4	0.06	...	...	...
NGC 2300	E3	1963	2.82	11.77	256	$52.0^{+30}_{-47.5}$	$0.23^{+0.33}_{-0.10}$	1.0	4.65	12/12	44.9	...	...	...
IC 455	S0	1887	1.1	14.01	...	...	...	...	...	...	...	...	...	...
Intragroup medium	...	2074	...	...	2698	$3.2^{+1.3}_{-1.1}$	$0.86^{+0.15}_{-0.14}$	$0.06^{+0.12}_{-0.05}$	71.4	22/25	23.8	60.0	1.3	9.0

Col (1).—Galaxy or object name.

Col (2).—Hubble type: for NGC 2276 and NGC 2300, taken from Sandage & Tammann 1987 [RSA2]; for IC 455, taken from de Vaucouleurs et al. (1991 [RC3]).

Col (3).—Optical heliocentric radial velocity (RC3) for galaxies; heliocentric group velocity for intragroup medium.

Col (4).—Optical isophotal diameter at $B = 25$ mag arcsec^{-2} (RC3).

Col (5).—Total apparent B-magnitude (RC3).

Col (6).—Total PSPC counts taken between 0.14 and 2.24 keV.

Col (7).—Best-fit H I column density, in units of 10^{20} cm^{-2}, from a Raymond-Smith 1977 plasma model fitted to the observed PSPC spectrum; errors are at the 90% confidence level.

Col (8).—Best-fit kT values, in keV, from Raymond-Smith model; errors are at the 90% confidence level.

Col (9).—For intragroup medium, best-fit abundance of hot gas (solar units); errors are at the 90% confidence level. For the galaxies this value is assumed to be unity.

Col (10).—Total observed X-ray flux, in units of 10^{-13} ergs cm^{-2} s^{-1}.

Col (11).—The goodness of fit of the Raymond-Smith plasma model.

Col (12).—Bolometric X-ray luminosity, in units of 10^{42} ergs s^{-1}. Distance to group is obtained by adding the Local Group radial velocity correction of 209 km s^{-1} (de Vaucouleurs, de Vaucouleurs, & Corwin 1976 [RC2]) to the quoted heliocentric radial velocity, and assuming a Hubble constant of $H_0 = 50$ km s^{-1} Mpc^{-1}.

Col (13).—Predicted bolometric X-ray luminosity, in units of 10^{42} ergs s^{-1}, based on the σ-L_x model of Edge & Stewart 1991.

Col (14).—Predicted X-ray temperature, in keV, based on the σ-T_x relation of Edge & Stewart 1991.

Col (15).—Predicted X-ray bolometric luminosity, in units of 10^{42} ergs s^{-1}, based on the L_x-T_x relation of Mushotzky 1984.

model (Jones & Forman 1984). The radial profile indicates that the diffuse emission can be traced to a radius of 25′ (∼0.3 Mpc) (Fig. 2). The existence of this diffuse emission is significant at better than the 99% confidence level.

The possibility that the diffuse emission may be due to extended halos from point sources in the field was tested by repeating the extraction and analysis excluding a region 3′ in radius around each source; no significant change in diffuse emission was found. In addition, no diffuse component was found when we performed the same extraction procedure on two other *ROSAT* fields of similar exposure time that contain X-ray emission from active galaxies, which rules out problems due to background subtraction and instrumental effects.

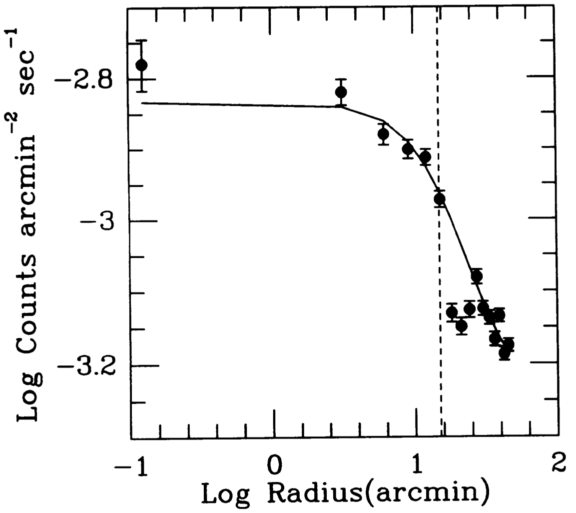

FIG. 2.—Radial distribution of emission from the diffuse gas in HG92, derived assuming radial symmetry. At the assumed distance of this group (45.7 Mpc), 15′ corresponds to 0.2 Mpc. Error bars are calculated from the rms deviation of the mean. The solid line is the best-fit isothermal model. The dashed vertical line indicates the radius at which the group's mass is calculated (see § 4). The points in the 15′–25′ range are artificially low because of the supporting rib structure of the PSPC window.

The spectrum of the diffuse gas was extracted by summing the counts in the inner 25′ of the field (derived as described above) and subtracting a background from an annulus 25′–35′ in radius. The intragroup medium spectrum is corrected for vignetting. Spectral fits were performed using the latest version of the PSPC spectral response matrix. Energy channels between 0.14 and 2.24 keV were used in the spectral analysis. A systematic error of 1% was added to the data, as recommended in the 1992 August 1 MPE News Bulletin.

3. SPECTRAL RESULTS

The spectrum of the diffuse gas in the group is shown in Figure 3*a*. A Raymond-Smith (1977) plasma model with variable abundance and N_{H} was fitted to this spectrum, with results given in Table 1 and the residuals of the fit displayed in Figure 3*b*. The X-ray–absorbing H I column density implied by the fit is $N_{\mathrm{H}} = 3.2^{+1.3}_{-1.1} \times 10^{20}$ cm^{-2}, lower than the Galactic line-of-sight value, $N_{\mathrm{H}}^{\mathrm{Gal}} = 5.6 \times 10^{20}$ cm^{-2} (Stark et al. 1992), but within 2 σ of this value. The temperature for the diffuse gas derived with the fitted H I column is $\sim 0.9^{+0.15}_{-0.14}$ keV ($T \sim 10^7$ K). Forcing the data to fit the Stark et al. (1992) column reduces the temperature to $0.69^{+0.15}_{-0.12}$ keV. The abundance of the diffuse emission ranges from 0.01 to 0.18 solar at 90% confidence. The confidence contours for the best-fit model in the abundance-kT plane are shown in Figure 4.

Spectra for the individual galaxies were extracted from a circle of radius 1′.5 centered on each target. The background was estimated from an annulus centered on the source with inner radius 1′.5 and outer radius 3′. The X-ray spectrum of each galaxy was fitted with several simple models and absorbing columns (Table 1). For NGC 2300 the best fit is provided by a Raymond-Smith plasma model with an H I absorbing column ∼1 σ higher than Galactic H I, albeit with a large estimated error. The X-ray emission from NGC 2276 is considerably softer than most spiral galaxies (Kim, Fabbiano, &

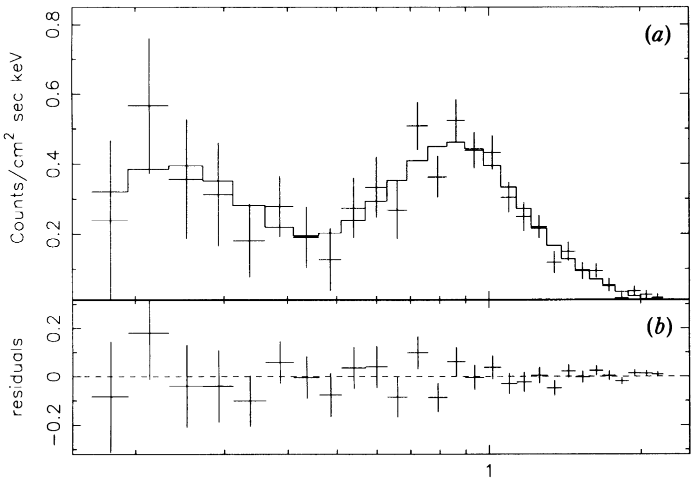

FIG. 3.—(*a*) X-ray spectrum of emission from the diffuse gas in HG92 (individual points with error bars) plotted together with the best-fit Raymond-Smith model (see Table 1 and text). (*b*) Residuals from the best-fit model, explicitly showing the goodness of fit.

Trinchieri 1992), which may be due to ongoing star formation and recent supernovae (see § 4).

4. DISCUSSION

Large surveys of clusters of galaxies have shown that there are strong correlations among the X-ray properties of the diffuse intracluster medium (ICM) (e.g., luminosity, temperature, gas mass) and optical properties of the cluster (e.g., velocity dispersion, galaxy number density, spiral galaxy fraction; Bahcall 1977a, b; Quintana & Melnick 1982; Rothenflug & Arnaud 1985). The most complete X-ray spectral survey to date is that of Edge & Stewart (1991), who find the X-ray/optical correlations for clusters with $kT > 2$ keV. Listed in Table 1 are predictions of T_x and L_x from the Edge & Stewart cluster σ-T_x and σ-L_x relations, and the L_x-T_x relation of Mushotzky (1984). We estimate that $\sigma \approx 300$ km s^{-1} for HG92, based on the radial velocities of four galaxies (including IC 455). One can see that while the Edge & Stewart relations reasonably predict T_x, they overestimate L_x. The L_x-T_x relation of Mushotzky (1984) works better for this group.

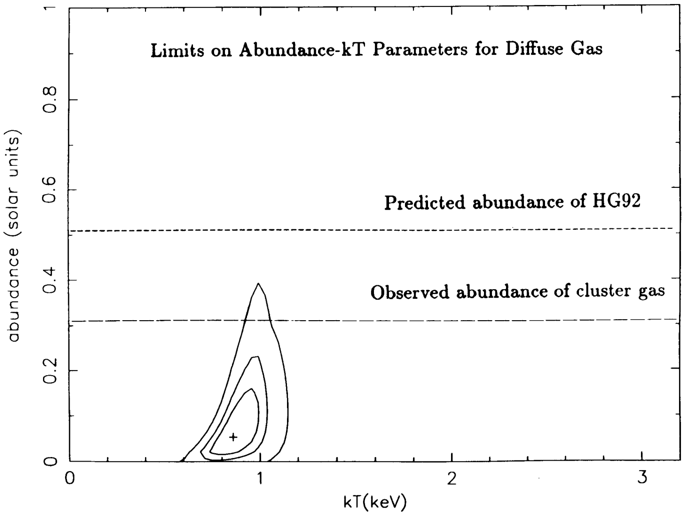

FIG. 4.—Contour plot of the Raymond-Smith model fitting parameters in the abundance-kT plane. The three contours represent the 68%, 90%, and 99% confidence levels for these two parameters. The cross marks the best-fit value (Table 1). The lower, long-dashed horizontal line represents the average abundance for the diffuse gas in clusters (Butcher & Stewart 1991). The upper, short-dashed line represents the value of abundance predicted for the diffuse gas of HG92 from the kT-abundance correlation found for clusters (Butcher & Stewart 1991).

Calculations for clusters of galaxies suggest that the "observable" matter (i.e., galaxies + ICM) accounts for less than half of the total cluster mass, requiring substantial amounts of dark matter (cf. Mushotzky 1991). The need for dark matter in groups of galaxies is more uncertain due to unknown group dynamics (cf. Trimble 1987). Using the assumptions of hydrostatic equilibrium, spherical symmetry, and an isothermal temperature distribution (assumptions also made for estimating cluster masses; see Cowie, Henriksen, & Mushotzky 1987), the total mass ($M_{\rm total}$) of the group within a given radius can be calculated directly. From the temperature found from the spectral fit, the total mass of the NGC 2300 group within a core radius of 15′ (=0.2 Mpc) is $3.0^{+0.4}_{-0.5} \times 10^{13}\,M_\odot$.

From the best Raymond-Smith model (Table 1), the number density for a uniform distribution of diffuse gas is $5.3^{+1.1}_{-1.0} \times 10^{-4}$ cm^{-3} at $r < 25'$. Assuming a constant gas density yields a firm upper limit of $5 \times 10^{11}\,M_\odot$ for the diffuse gas mass within a radius of 0.2 Mpc from the center of emission. An estimate for the baryonic mass in the three galaxies ($M_{\rm gal,\,bary}$) can be made by assuming $M/L_B = 8.5$ for E and S0 galaxies (Faber & Gallagher 1979) and 2.6 for Sc galaxies (Burstein & Rubin 1985), with 20% of the E and S0 mass being dark and 50% of the spiral mass dark. From this, we estimate $M_{\rm bary,\,gal} \approx 6 \times 10^{11}\,M_\odot$.

With $H_0 = 50$ km s^{-1} Mpc^{-1}, baryonic matter comprises less than 4% of the total mass in the group within a 0.2 Mpc radius of the center of the X-ray emission. Cowie et al. (1987) estimate that cluster masses derived from X-ray data can be in error by no more than 50%. Similarly, the distance to the group cannot be in error by more than 50%. Even if the errors in total mass and distance operate in the same direction, the baryonic mass fraction in HG92 is not more than 10%–15%. We conclude that the existence of diffuse gas in this group is one of the strongest pieces of evidence yet that galaxies in small groups lie in gravitational potentials dominated by dark matter. Our best estimate of the ratio of baryonic matter to dark matter in HG92 ranges from 0.02 to 0.06, close to the ratio predicted by the standard big bang nucleosynthesis model, $0.04 < \Omega_{\rm baryonic} h_{50}^2 < 0.08$ (Steigman 1989, with $h_{50} = H_0/50$). Thus, small groups of galaxies may be the portion of the universe which retains the primordial ratio of dark to baryonic matter.

Where does the diffuse gas in HG92 originate? The low abundance of the diffuse gas relative to that in clusters ($\sim$0.06 compared with 0.3 solar; Butcher & Stewart 1991) goes against the trend for low-luminosity clusters of galaxies to be metal-rich (Yamashita 1992), and makes this the lowest abundance intergalactic gas known. Moreover, the ratio of diffuse gas mass to galaxy mass in HG92 is $\sim$1, an order of magnitude lower than this ratio in clusters, but consistent with the trend for low-luminosity clusters to have a lower ratio (David et al. 1990). Either galaxies in HG92 contributed relatively less enriched material to the intragroup medium than the galaxies in clusters, or this kind of small group is more easily contaminated by primordial gas from outside the group than are clusters.

It has been suggested that galaxy-gas interactions can affect a galaxy in ways besides gas stripping, including stimulating star formation within the disk of a spiral and distorting the galaxy's optical and radio morphologies (Condon 1983; Cayatte et al. 1990; Kotanyi, Van Gorkom, & Ekers 1983). For NGC 2276 the optical morphology is odd enough to place it in Arp's (1966) Atlas of Peculiar Galaxies. The western side of the galaxy has a sharp curved boundary shaped like a "bow shock." This edge contains over a dozen bright blue "knots" of emission (Shakhbazyan 1973) and has been the site of three historic supernovae (Barbon, Cappellaro, & Turatto 1989). Apparently a strong burst of star formation is occurring along this edge.

Condon (1983) suggested that interaction with a hot intergalactic gas might naturally explain the "strikingly swept-back appearance" of the radio continuum emission in NGC 2276. Our direct detection of an intragroup medium strongly supports this view. Even if NGC 2276 were at the densest portion of the intragroup medium, the ram pressure (i.e., ρv^2) is not likely to exceed the gravitational force binding the ISM to the galaxy (cf. eq. [5.114] in Sarazin 1986). Consistent with observations, however, such an encounter should perturb the interstellar medium in the outer portions of the disk (cf. Kenney 1990). Similar optical morphologies are found in other spirals in nearby groups, suggesting a similar origin.

5. CONCLUSIONS

The detection of a hot intragroup medium in a normal group of galaxies is supported by the following evidence: (1) Diffuse emission is detected near the center of the group, at a position that is offset from the center of the *ROSAT* field. (2) No "diffuse" component was found when our extraction method was applied to two comparable *ROSAT* fields. (3) A Raymond-Smith (1977) plasma model provides an excellent fit to the spectrum of the diffuse emission. (4) The linear size of the X-ray emission extends beyond the region occupied by the three group galaxies. (5) The temperature and X-ray luminosity of the gas follow the relations found for cluster gas. (6) The spiral galaxy NGC 2276 shows morphological evidence for an intragroup medium–galaxy encounter.

The diffuse X-ray emission extends to a radius of at least 0.2 Mpc. The temperature and X-ray luminosity of the hot gas are $\sim 0.9^{+0.15}_{-0.14}$ keV ($T \sim 10^7$ K) and $(2.3 \pm 0.1) \times 10^{42}$ ergs s^{-1}, respectively. This temperature, combined with the assumption of gravitational confinement, leads to a total mass of the group of $3.0^{+0.4}_{-0.5} \times 10^{13}\ M_\odot$ within the core radius (=0.2 Mpc). A calculation of the baryonic mass indicates that less than 4% of the mass in this group is baryonic. Errors could conspire to raise this percentage to, at most, 10%–15%. These X-ray observations establish, in a manner independent of kinematic arguments, that the mass of this group is dominated by dark matter. To our knowledge, this is the first system for which the observed ratio of baryons to dark matter is consistent with $\Omega = 1$ and the baryonic ratio implied by the standard model of big bang nucleosynthesis. However, similar values of $M_{\mathrm{bary}}/M_{\mathrm{dark}}$ may be found in the *cores* of a few rich clusters (Edge & Stewart 1991).

The intragroup medium of HG92 has an abundance ~0.06 solar, making it the lowest abundance diffuse gas observed to date. The gas appears to be of sufficient density to perturb the interstellar medium in the spiral galaxy NGC 2276. This encounter could account for the asymmetric, bowshock-like appearance of this galaxy and the strong burst of star formation it is experiencing. That other spirals in nearby groups have optical morphologies similar to NGC 2276 suggests that gas-galaxy encounters may be common.

The ability to constrain the spectral properties of the intragroup medium adequately in the NGC 2300 group of galaxies allows us to address the distribution of mass and the evolution of group members in ways previously not possible. Similar analysis of *ROSAT* archival data on other poor groups will demonstrate whether this phenomenon is common or is restricted to a few peculiar objects.

The authors thank Andy Fabian for reminding us of the ratio of baryonic to dark matter in the cores of rich clusters. We also acknowledge Michael Regan and Skip Westphal for their help in preparing Figure 1. The optical image in Figure 1 was produced with GASP. J. S. M. acknowledges support from a STScI graduate student assistantship.

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Note added in proof.—There is an error in the mass and the size of the X-ray emission in the abstract, discussion, and conclusion sections. The minimal extent of the X-ray emission is 25′ (0.29 Mpc), and the mass within this radius is $\sim 2 \times 10^{13}\ M_\odot$. The dotted line in Figure 2 should lie at log radius = 1.4.