THE ASTROPHYSICAL JOURNAL, 418:L55–L58, 1993 December 1

THE HEAVY ELEMENT ABUNDANCE IN THE HOT CORONA OF THE BRIGHT ELLIPTICAL GALAXY NGC 4472

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Received 1993 July 19; accepted 1993 September 17

ABSTRACT

From a 25 ks *ROSAT* PSPC observation of the elliptical galaxy NGC 4472, we measured the iron abundance with arcminute spatial resolution to a radial distance of 16′ (74 kpc) in the hot corona. The heavy element abundance is roughly constant at approximately 1–2 $[Fe/H]_\odot$ from 4′ to 16′. A comparison of these measurements to models of the heavy element enrichment of hot galactic coronae around elliptical galaxies provides new insights and constraints for the evolution with time of the Type Ia supernova rate and for its present epoch value. In particular, the near-solar value of the iron abundance and its constancy throughout the corona suggest a relatively constant supernova rate over time with a present epoch value at the low end of the range derived by van den Bergh & Tammann.

Subject headings: galaxies: abundances — galaxies: individual (NGC 4472) — galaxies: ISM — X-rays: galaxies

1. INTRODUCTION

The discovery of hot coronae, with gas masses up to 10^{10} $M_\odot$, around early-type galaxies (Forman et al. 1979; Nulsen, Stewart, & Fabian 1984; Forman, Jones, & Tucker 1985) dramatically changed our view of these galaxies and showed that the bulk of their interstellar matter was hot ($kT \sim 0.5$–1.0 keV) and readily detectable in X-rays. The hot coronae opened new avenues for exploration of early-type galaxies and led, most notably, to the conclusion that these systems require massive dark halos to bind the X-ray–emitting gas (Forman et al. 1985; Fabian et al. 1986; Mathews & Loewenstein 1986; Sarazin & White 1988; David, Forman, & Jones 1991; Loewenstein 1992).

The hot corona, as the repository of the stellar mass loss (that not expelled from the galaxy or recycled into stars), contains a fossil record of past supernova activity in the galaxy. Since the radial flow time of the gas is billions of years, the hot gas at any radius contains a history of the metals injected into it by evolving stars. As Loewenstein & Mathews (1991) emphasized, measuring radial abundance gradients determines both the history of the past supernova rate, as well as its present value. Abundance measurements also distinguish among different models for the gas dynamics in the corona. For example, predicted abundances in long-lived wind models (D'Ercole et al. 1989) exceed several times the solar value and can readily be distinguished from those with nearly solar abundances expected in quasi-hydrostatic or inflow models (Loewenstein & Mathews 1987; David et al. 1991).

The first studies of heavy element abundances in hot coronae were reported for NGC 4636, NGC 1399/Fornax, and NGC 4472 (Awaki et al. 1991; Loewenstein 1991; Ikebe et al. 1992; Jones et al. 1992; Serlemitsos et al. 1993). For NGC 4472 and NGC 4636, the *Ginga* observations gave only upper limits on the iron abundance, while the BBXRT observation of NGC 4472 provided only a single measurement. For NGC 1399, which lies at the center of a rich group, the Fornax cluster, BBXRT observations provided measurements of the inner cooling region and an "outer" region, while the *ROSAT* analysis should provide comparable results to those reported here for NGC 4472. Hence, the results reported here are the first heavy element abundance determinations, of an early-type galaxy, with adequate sensitivity to measure the heavy element abundance with arcminute spatial resolution over the ~ 100 kpc region of a hot corona. These observations provide unique insights into the evolution of the underlying stellar population.

NGC 4472 is representative of early-type galaxies, and, although relatively bright in both X-rays and optical light, it lies almost exactly on the best-fitting correlation of optical luminosity versus X-ray luminosity (e.g., Donnelly, Faber, & O'Connell 1990). Thus, although NGC 4472 lies near a loose concentration of galaxies in the southern portion of the Virgo cluster (Binggeli, Tammann, & Sandage 1987; Huchra 1990), its X-ray emission and hence its corona are typical of a galaxy rather than of a "central cluster galaxy" like M87 which is almost 100 times brighter in X-rays and has a higher gas temperature.

In this *Letter* we show that the iron abundance in the corona of NGC 4472 is about 1–2 times the solar value within a radius of 16′ which corresponds to 64–115 kpc (for distances to NGC 4472 of 14–25 Mpc which are typical of the range of quoted distances: Tonry, Ajhar, & Luppino 1989 and references therein; Sandage & Tammann 1981; Donnelly et al. 1990). As we discuss, this suggests that the present epoch Type Ia supernova rate in consistent with values at the low end of the range derived by van den Bergh & Tammann (1991). In addition, evolutionary models with strong decreases in the supernova rate with time, such as those proposed by D'Ercole et al. (1989) are not consistent with the approximately solar abundances measured in the corona.

2. OBSERVATIONS AND DATA ANALYSIS

We observed NGC 4472 for 25.971 ks with the *ROSAT* PSPC. We first examined background regions as a function of time during the observation, but found no intervals of high background that required excision from the image. We identified all significant pointlike sources in the PSPC field of view and excluded these source regions from both the NGC 4472 radial regions and the background regions used for determining the net pulse height spectra. Background regions were chosen 30′–40′ from the field center. The counts in each background pulse height channel were vignetting corrected to the off-axis distance of each annulus around NGC 4472. When we examined the outer annulus from 14′ to 16′, we found that the background subtraction resulted in net negative counts below 0.3 keV, probably because the source point-spread function is so large at the background radius (>30′ off axis) that weak sources cannot be detected. To correct for this oversubtraction, we reduced the amount of background subtracted by 5%.

For each annulus, the observed source spectrum was compared to models of an optically thin thermal spectrum. We exclude the lowest and highest energy channels and use the energy range from 0.17 to 1.91 keV. The free parameters in each fit included the gas temperature, the hydrogen column density, the elemental abundance (we vary the abundance of all elements heavier than helium but keep their relative abundances with respect to each other fixed at the solar value), and the normalization of the model. Note that while the abundances of all the elements heavier than helium are varied (with solar ratios), the emission lines of iron dominate the spectrum at temperatures around 1 keV, and hence the measured constraint is for iron. To determine uncertainties in the spectral parameters, we first allowed all the free parameters to vary and determined the change in the interesting parameter corresponding to a desired change in $\Delta\chi^2$. We use the prescription of Avni (1976) and Lampton, Margon, & Bowyer (1976) such that a 1 σ (68% confidence interval) for one interesting parameter (the abundance for the purposes of this *Letter*) corresponds to $\Delta\chi^2 = 1$. Although the value of $\Delta\chi^2$ is appropriate for a single parameter, when we evaluated the confidence region, all the parameters were free to vary. Hence, correlations between the parameters are properly taken into account when we determined the confidence region. The hydrogen column density showed no evidence of variability over the galaxy, and the values measured in each annulus were consistent with the galactic value (1.64×10^{20} cm^{-2}; Stark et al. 1992). We also performed model fits in which we held the hydrogen column density fixed at the galactic value. The results of our measurements of the iron abundance are shown in Figure 1.

Table 1 (for the hydrogen column density as a free parameter) provides a full set of fitted parameters and uncertainties including the hydrogen column density, the gas temperature, and the heavy element (iron) abundance. The heavy element abundances are approximately constant with radius. Note that the observational data points are the mean projected along the line of sight, while the theoretical models are the values in a spherical shell around the galaxy. Because the surface brightness falls rapidly with radius ($S \propto r^{-2}$), the emission in projection is dominated by the emission from the innermost shell, and hence the observations should be a good approximation of the model. Within 4′, the abundance deter-

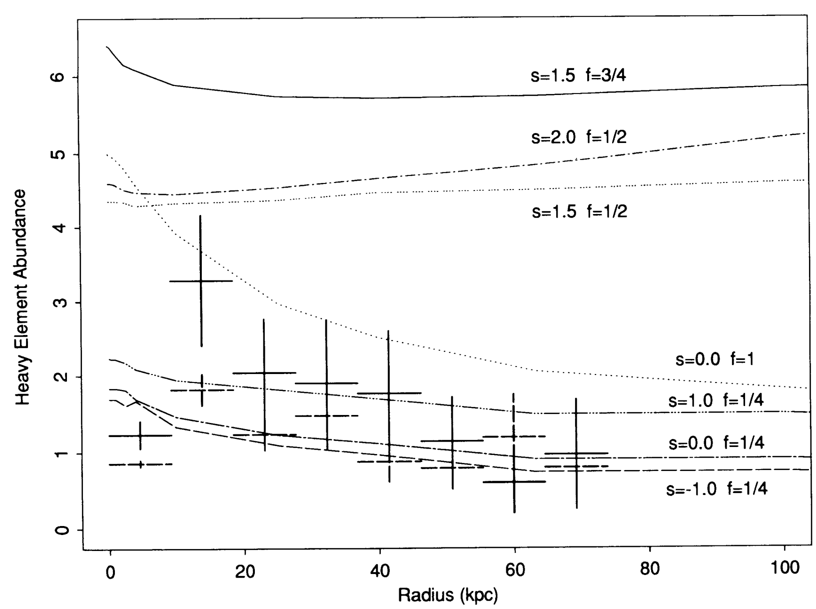

FIG. 1.—Distribution of the heavy element (iron) abundance measurements as a function of radial distance from the center of NGC 4472 (*solid crosses*) assuming a distance of 16 Mpc. We also show (*dashed crosses*) the values of the heavy element abundance derived by holding the column density fixed at the galactic value ($n_H = 1.64 \times 10^{20}$ cm^{-2}). The error bars indicate the 68% confidence error bars ($\Delta\chi^2 = 1$ with all parameters free to vary). In addition, we have shown several curves indicating the expected distribution of the heavy element abundances derived from the hydrodynamical model calculations of Loewenstein & Mathews (1991). Note that the observational data points are the mean projected along the line of sight, while the theoretical models are the values in a spherical shell around the galaxy. Because the surface brightness falls rapidly with radius ($S \propto r^{-2}$), the emission in projection is dominated by the emission from the innermost shell, and hence the observations should be a good approximation of the model.

mination may be biased, since gas in this region may be cooling significantly. The temperatures in the inner two annuli are less than in the outer part of the galaxy as can be seen by comparing the temperature given in Table 1. Also, averaging the data from 4′ to 16′ yields $kT = 1.18 \pm 0.05$ keV (where the error gives the 90% confidence range). Hence, significant radiative cooling of the gas could be occurring in these inner regions, particularly within a 2′ radius, as suggested by Thomas et al. (1986), and single-temperature models are probably inappropriate. Cooling gas can give rise to complex abundance gradients. For example, as the gas first begins to cool below the temperatures measured in the outer 4′–16′ of NGC 4472, the emission from the iron lines increases. However, as the gas continues to cool and fall toward the center of the galaxy, the cooling time will become less than the recombination time, and the gas will no longer be in ionization equilibrium. Hence, in the very central regions, the cold electrons can no longer excite the highly ionized atoms, and the line emission decreases. Note that beyond a radius of 4′, the gas cooling time exceeds 3×10^9 years, and hence infall cannot be significant. When the hydrogen column density is a free parameter, beyond 2′ (see results of fits in Table 1), there is an apparent trend of decreasing abundance with increasing radial distance from NGC 4472. However, when the hydrogen column density is held fixed over all annuli at the galactic value, no significant change in the abundance with radii is observed. A better understanding of the *ROSAT* instrument (or observations with another instrument) is necessary to confirm the suggestion of a change in abundance with galaxy radius.

3. DISCUSSION

The present epoch supernova rate in elliptical galaxies is quite poorly constrained. Still less is known regarding the time dependence of this rate. Ciotti et al. (1991) argued that a rapid decline in the supernova rate with time is warranted based on either of two mechanisms for the origin of Type Ia supernova–Roche lobe overflow of an evolving star onto a white dwarf or the merger of two white dwarfs driven by gravitational radiation. Other models of the evolution of hot coronae (Loewenstein & Mathews 1987; David, Forman, & Jones 1990) derived a considerably weaker dependence of the supernova rate on time.

The nearly solar abundance of heavy elements over a wide range in radii observed in NGC 4472 eliminates models which predict heavy element abundances much in excess of the solar value. For example, to account for the very large dispersion in X-ray luminosity (at a given optical luminosity) seen in the correlations of X-ray and optical luminosity, D'Ercole et al. (1989; see also Ciotti et al. 1991) proposed a model in which the Type Ia supernova rate decreases rather rapidly over time. Subsequently, Donnelly et al. (1990) showed that more accurate distances and magnitudes substantially reduced this dispersion. The D'Ercole et al. models produce hot coronae which are characterized by galactic winds over much of the galaxy lifetime and which eventually become quasi-hydrostatic inflows as the supernova rate declines. The most massive (luminous) galaxies are the first to revert from winds to inflows. However, these models produce very high heavy element abundances. For a typical model of 10^{11} $L_\odot$ galaxy, Ciotti et al. (1991) derive a heavy element abundance of 3.7 times solar in the corona at the present epoch which conflicts with the abundances measured.

A general investigation of the dependence of the heavy element abundances in hot coronae on the supernova rate was carried out by Loewenstein & Mathews (1991). They characterized the time dependence of the Type Ia supernova rate and its present epoch value with an expression of the form $R_{SN} = 2.2f(t/t_H)^{-s}$ where R_{SN} is the number of Type Ia supernovae per 100 years per 10^{11} $L_\odot$, t_H is the present time, f is the ratio of the present epoch supernova rate to that given by Tammann (1974), and s parameterizes the dependence of the supernova rate with time. The D'Ercole et al. models are characterized by $s = 1.4$. In Figure 1 we have superposed several of their model calculations which show the derived radial behavior of the heavy element abundance for a family of galaxy models for a 10^{11} $L_\odot$ galaxy with a heavy halo. A luminosity of 10^{11} $L_\odot$ is appropriate to NGC 4472 since its luminosity ranges from 0.6 to 1.8×10^{11} $L_\odot$ for the range of distances cited above. The stellar iron abundance profile assumed by Loewenstein & Mathews (1991) was computed from the Mg distributions (derived by Thomsen & Baum 1989 for three Coma ellipticals) and assumes solar abundance ratios. The resulting stellar iron distribution has a central abundance of twice solar and decreases slowly with radius. This is consistent with observations of NGC 4472 as given by Gorgas et al. (1990). Worthey, Faber, & Jesus Gonzalez (1993) showed that iron is on average underabundant by a factor of 1.6–2.0 compared to magnesium in the stellar component of giant elliptical galaxies. This would reduce the iron abundances shown in the model curves of

TABLE 1

RESULTS OF SPECTRAL FITTING FOR NGC 4472[a]

Annulus (arcmin)	Annulus (kpc)	Net Counts[b] (0.2–2.20 keV)	Temperature (keV)	Hydrogen Column ($\times 10^{20}$ cm^{-2})	Abundance (solar)
0–2	0.0–10.3	12097 ± 111	0.87–0.88	0.97–1.32	1.05–1.41
2.4	10.3–20.6	6133 ± 84	1.03–1.05	0.64–1.15	2.40–4.16
4–6	20.6–31.0	4588 ± 80	1.10–1.16	0.58–1.40	1.31–2.76
6–8	31.0–41.3	3632 ± 81	1.14–1.21	0.74–2.08	1.05–2.75
8–10	41.3–51.6	3529 ± 87	1.11–1.21	0.22–1.22	0.92–2.60
10–12	51.6–61.9	3481 ± 97	1.17–1.35	0.54–1.88	0.57–1.71
12–14	61.9–72.2	3193 ± 105	1.12–1.44	0.20–7.56	0.20–1.00
14–16	72.2–82.7	3231 ± 116	1.07–1.42	0.56–3.27	0.25–1.68

[a] The range in parameters corresponds to 68% confidence for one parameter as described in the text. All parameters are varied simultaneously when determining the error range.

[b] The source luminosity for the region interior to 16′ is 3.7×10^{42} ergs s^{-1} (for an assumed distance of 16 Mpc).

Figure 1 by less than 0.5 (in solar units). Such a change, if required, is sufficiently small that it would not affect any of our conclusions. However, we have verified that for NGC 4472 iron may not be significantly underabundant with respect to magnesium. Using iron and magnesium absorption line strengths from Davies, Sadler, & Peletier (1993) with the calibration from Worthey (1992), we find abundances of 1–1.6 solar at half an effective radius for assumed stellar population ages between 12 and 17 Gyr. Thus, although these optically determined heavy element abundances apply only to the central regions of the galaxy where the X-ray spectrum is complicated by the effects of radiative cooling (and cannot be directly compared to the X-ray measurements), they are in agreement with the values used in the model calculations.

It is apparent from Figure 1 that models with much higher supernova rates at earlier epochs conflict with the observations reported here. In particular, models in which the supernova rate is characterized by $s \geq 1.5$ predict heavy element abundances in excess of that observed. The models which most closely describe the observations are those with constant or slowly varying supernova rates ($|s| < 1$), and even these require relatively modest values of the present epoch supernova rate. Comparing the curves for the two models with $s = 0$ in Figure 1 shows that present epoch values equal to van den Bergh & Tammann's (1991) rate ($f \sim 1$) produce iron abundances in excess of those observed, while predicted iron abundances for $f = \frac{1}{4}$ (again for $s = 0$) are in good agreement with the observations. Hence, in the context of the existing models for elliptical galaxies (i.e., those with heavy halos), the observations argue for a constant or at most a slowly varying supernova rate ($|s| < 1$). The observations also suggest that the present epoch supernova rate is significantly less than $f = 1$ (in good agreement with the van den Bergh, McClure, & Evans 1987 value and consistent with the lower range of values derived by van den Bergh & Tammann 1991). Note that higher supernova rates are possible if the iron yields from Type Ia supernovae are reduced or if the ejecta are not completely mixed into the hot ISM before cooling. Also, in the absence of heavy halos, the abundance observations could be matched by a wider range of values of s and f. However, these models would conflict with the X-ray–measured gas temperature and gas density profiles which require the presence of heavy halos.

We also can conclude that the gas surrounding NGC 4472 has not been stripped from the galaxy at an earlier epoch by passing through the cluster core or mixed with intracluster gas from the core of the Virgo cluster. First, if the gas originating around NGC 4472 were stripped by the ram pressure of the gas in the Virgo core region, the Virgo gas is too hot to be accreted onto NGC 4472 given its low gas temperature (see Table 1) and its inferred gravitational mass. Second, if NGC 4472 had crossed through the core of the Virgo cluster, the group of galaxies and NGC 4472 itself would be tidally limited to a size of only a few tens of kiloparsecs (Merritt 1984). Such an interaction would disperse the galaxy group surrounding NGC 4472 and would have removed the bulk of the mass observed around it. Thus, we can have some confidence that the gas we observe was produced in a manner consistent with the scenarios assumed in generating the models.

In summary, the rejection of models with rapidly decreasing supernova rates also has implications for the origin of Type Ia supernovae. The rejection of models with high iron abundances implies the rejection of models in which the Type Ia supernova rate decreases substantially in time. This in turn means that scenarios for Type Ia supernovae which predict such a dependence of the supernova rate with time can be rejected.

The above conclusions remain tentative since the models may not be fully realistic, and effects not included in the calculations could alter the derived heavy element abundance distributions. For example, the mixing of stellar and supernova ejecta into the hot coronal gas may be incomplete, and thus the heavy elements produced from each process may not be injected completely into the corona. Further complications are the nonsolar abundance ratios and the dispersion in these ratios (Worthey et al. 1992). With more detailed modeling, observations of additional galaxies with a range of optical luminosity (mass) and over a range of redshift (look-back time), and observations having higher spectral resolution to measure abundances of individual heavy elements, we will better understand the properties of elliptical galaxies, the evolution of their hot coronae, and the evolution of their stars and supernovae which determine the mass and energy balance of the hot coronae.

This work is supported by the Smithsonian Astrophysical Observatory and NASA contracts and grants, NAS 8-39073 and NAG 8-1536. We thank the referee for helpful comments.

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