New Measurement of Metal Abundance in the Elliptical Galaxy NGC 4636 with ASCA

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ABSTRACT

High-quality X-ray spectra of NGC 4636 are obtained with ASCA. Theoretical models are found unable to reproduce the data in the Fe-L line region. Spectral data above 1.4 keV indicate that the Mg to Si abundance ratios are almost solar. Assuming that the abundance ratios among α elements are the same as the solar ratios, a spectral fit with increased systematic error in the 0.4–1.6 keV range gives abundances of α elements and Fe to be both approximately solar by taking 1 solar of Fe to be by number. These new abundance results solve the discrepancy between stellar and hot-gas metallicities, but still a low supernova rate is implied. We also detect strong abundance gradients for both α elements and iron in a similar fashion. The abundance is ~1 solar within 4’ and decreases outward down to 0.2–0.3 solar at 10’ from the galaxy center. Dilution due to an extended hot gas is suggested.

Subject headings: galaxy: abundance — galaxies: individual (NGC 4636) — X-rays: galaxies

1. INTRODUCTION

The interstellar medium (ISM) of elliptical galaxies is considered to be an accumulation of stellar mass loss and supernova ejecta. While standard supernova rates predict the ISM to have a metallicity of several times the solar value (e.g., Loewenstein & Mathews 1991; Renzini et al. 1993), the observed ISM metallicity in fact falls below half solar, even lower than the stellar metallicity (e.g., Awaki et al. 1994; Mushotzky et al. 1994; Matsushita et al. 1994; Arimoto et al. 1997; Matsumoto et al. 1997). This strong discrepancy calls into question our current understanding of supernova enrichment and chemical evolution of galaxies.

NGC 4636 is one of the relatively isolated yet most luminous elliptical galaxies, both in optical ($L_\odot = 2.9 \times 10^{10} L_\odot$, assuming a distance of 17 Mpc), and in the X-ray ($L_x = 3.8 \times 10^{41}$ erg s$^{-1}$; Einstein) band (e.g., Forman et al. 1985; Fabbiano et al. 1992). Using ROSAT, Trinchieri et al. (1994) discovered a very extended X-ray emission surrounding this galaxy, out to ~18’. The first ASCA observation of NGC 4636 in the performance verification (PV) phase yielded the X low ISM metallicity (Awaki et al. 1994), together with abundance and temperature gradients (Mushotzky et al. 1994).

We have reobserved NGC 4636 with ASCA (Tanaka et al. 1994) for an extremely long time; over 200 ks. This has allowed Matsushita (1997) to perform a much deeper study of the extended X-ray component after ROSAT. In this paper, we utilize the overall ASCA data including this long exposure, to study the spectral properties of NGC 4636 and look into the abundance problem.

2. OBSERVATIONS

NGC 4636 has been observed from ASCA twice. Following the PV observation (1993 July 22, with the SIS in 4CCD mode), the second much longer observation was conducted in the AO-4 phase from 1995 December 28 through 1996 January 4, with the SIS in the 1CCD mode. We discarded the data taken under cutoff rigidities less than 6 GeV $c^{-1}$ or elevation angle less than 5° and 20° from night and day Earth, respectively. This has yielded exposure times of 36 ks (with the GIS) and 39 ks (with the SIS) for the PV observation, and those for the AO-4 observation are 172 ks (GIS) and 215 ks (SIS).

We accumulated on-source spectra within 4 times the effective radius, $r_e = 1.7$ (Faber et al. 1989), centered on NGC 4636. Since the SIS response has changed with time, we treat the SIS spectra from the two observations separately. The background spectrum was obtained by integrating the blank-sky data over the same region of the detector. Figure 1 shows the background-subtracted SIS spectrum for the AO-4 data.

3. RESULTS

We jointly fitted the two SIS (PV and AO-4) spectra and one GIS spectrum, with a standard two-component model (Awaki et al. 1994; Matsushita et al. 1994; Matsumoto et al. 1997). The model consists of a thin thermal emission from the ISM with free temperature $kT$ and free metallicity, and a thermal bremsstrahlung with temperature fixed at 10 keV representing the contribution from low-mass X-ray binaries. Both components are subjected to a common interstellar absorption $N_H$. Although the GIS (Ohashi et al. 1996; Makishima et al. 1996) is less sensitive than the SIS to the low-energy (e.g., <1 keV) atomic lines, it can constrain the hard component better than the SIS and is fully sensitive to the Si-K and S-K lines. Therefore, the joint use of the two instruments is essential. In this paper we adopt for the solar iron abundance the “meteoritic” value, Fe/H = $3.24 \times 10^{-3}$ by number (Anders & Grevesse 1989).

3.1. Problems with the Spectral Analysis

As the first-cut spectral analysis, we represented the ISM component by the plasma emission model of Raymond & Smith (1977, hereafter the R-S model) with solar abundance ratios. The best-fit model parameters turned out to be consistent with those of Awaki et al. (1994), but the fit was totally unacceptable (Table 1). We then allowed the abundances to deviate from the solar ratios, by dividing heavy elements into two groups to estimate relative contributions from Type Ia and Type II supernovae (SNe). One group consists of so-called α elements, O, Ne, Mg, Si, and S, which are assumed to have a common abundance $A_\alpha$. The other group includes Fe and Ni, with a common abundance $A_\beta$. The abundance of He is fixed to be
The abundances of the other elements are assumed to be the same as $\alpha$ elements, although their effect on 1 keV spectrum is negligible. The fit incorporating six parameters ($A_\alpha$, $A_\text{Fe}$, $kT$, $N_\text{H}$, and two normalizations) still remained far from acceptable, as shown in Table 1. We further replaced the R-S model with MEKA model (Mewe et al. 1985; Mewe, Lemen, & van den Oord 1986; Kastra 1992), MEKAL model (Liedahl, Osterheld, & Goldstein 1995), or Masai model (Masai 1984), but none of them were successful. Multitemperature ISM models did not improve the fit either.

In these fits, the data-to-model discrepancy is always largest around the Fe-L complex region (0.8–1.4 keV). In addition, the fitted residuals and the derived physical quantities both confirm the serious problems in the theoretical Fe-L line modeling, as pointed out by Fabian et al. (1994) and Arimoto et al. (1997). Furthermore, we have found strong false couplings between $A_\alpha$ and $A_\text{Fe}$, arising from the following two effects. On one hand, the fitting algorithm tries to reduce the Fe-L discrepancy, by adjusting intensities of the O-K and Ne-K lines that overlap the Fe-L complex; this strongly affects $A_\alpha$, since the data have the highest statistics in this energy range. In turn $A_\alpha$ affects $A_\text{Fe}$, because the bound-free emission from oxygen and neon acts nearly as a continuum to the Fe-L lines and controls their equivalent widths. These effects make both $A_\text{Fe}$ and $A_\alpha$ highly unreliable.

### 3.2. Abundance of $\alpha$ Elements

In order to avoid these problems, we tentatively restricted the energy range for the SIS spectral fit to greater than 1.4 keV, which is unaffected by the Fe-L, O-K, and Ne-K lines. For the GIS spectrum, we used an energy range above 1.6 keV, because of its poorer energy resolution.

We rearranged the heavy elements into four groups: Mg, Si, S, and other elements including O, Ne, Fe, and Ni (hereafter $A_\text{other}$). Elements in the last group contribute to the greater than 1.4 keV spectrum mainly via free-bound continua (Fe-K and Ni-K lines are undetectable). Then, the fit has become acceptable with the reduced $\chi^2$ of 1.06 for 220 dof. The derived temperature, 0.73 keV (0.67–0.76 keV with 90% confidence for a single parameter), agrees with those derived using the whole energy range. We have further found that the Mg to Si abundance ratio always agrees with the solar ratio (Fig. 2), even though their abundances correlate considerably with $A_\text{other}$. The S abundance may be similar, or slightly higher by about 30%. On the other hand, the stellar and supernova nucleosynthesis predicts O, Ne, and Mg to follow the solar abundance ratios (Thielemann, Nomoto, & Hashimoto 1996). Therefore, it is reasonable to assume that all the $\alpha$ elements (O, Ne, Mg, Si and S) have the same abundance in solar units.

We can now safely return to the original element grouping into $A_\alpha$ and $A_\text{Fe}$, and refit the spectra above 1.6 keV (SIS) and 1.7 keV (GIS). The fit is acceptable with the reduced $\chi^2$ of 1.06 for 210 dof, and the derived temperature is 0.75 (0.72–0.78) keV.

Now, $A_\alpha$ is determined relatively well (Fig. 3), because it relies upon the Si-K and S-K lines instead of using the unreliable O-K and Ne-K lines that are now ignored. Unlike the full-range fit, $A_\alpha$ depends on $A_\text{Fe}$ only weakly through Fe contribution to the free-bound continuum. These results unambiguously show that $A_\alpha$ is roughly 1 solar, unless $A_\text{Fe}$ is extremely high.
3.3. Iron Abundance

Our next task is to better constrain $A_{\text{Fe}}$. This requires us to utilize the Fe-L line information, but simply revolving the energy range below 1.6 keV would bring us back to the original problems described in §3.1. In order to relax the overly strong constraints imposed by the data in the Fe-L region, we have decided to assign 20% systematic errors to each spectral data in the 0.4–1.6 keV range. This is because the data-to-model discrepancy and the model-to-model differences are both ~20% around the Fe-L region (Masai 1997). We have thus fitted the SIS/GIS spectra jointly with the two-component model, incorporating the increased systematic error and again employing the element grouping into $A_{\alpha}$ and $A_{\text{Fe}}$.

The fit is acceptable with either of the plasma models (Table 1), and the confidence regions on the $A_{\alpha}$ vs. $A_{\text{Fe}}$ plane for different plasma emission codes have come to a similar region (Fig. 3). As a consequence, we can now conclude with confidence that $A_{\alpha}$ and $A_{\text{Fe}}$ are both consistent with ~1 solar, within a factor of 2. In addition, the ratio between $A_{\alpha}$ to $A_{\text{Fe}}$ coincides with the solar ratio within ~20%.

3.4. Metal Distribution in the ISM

In order to study the metal distribution, we accumulated the GIS and SIS spectra in three concentric annular regions with radius range, 0′–4′, 4′–8′, and 8′–12′ centered on the galaxy. We assume that the ISM is spherically symmetric. This “ring-shaped analysis” is, however, limited by the spectral mixing effect among different sky regions, due to the extended point spread function of the ASCA X-Ray Telescope (XRT; Serlemitsos et al. 1995). This tends to smear out any radial gradient in the ISM properties. Following the analysis in §3.3, we include 20% systematic error in the 0.4–1.6 keV data. We fitted only with the R-S model, since the difference due to plasma emission code is only several tens of percent after inclusion of the systematic error. An acceptable fit is obtained in all three regions (Table 2).

As shown in Table 2 and Figure 4, the derived $A_{\alpha}$ and $A_{\text{Fe}}$ are ~1 solar within $r < 4'$, and drop to 0.2–0.3 solar at $r ~ 10'$. This confirms the existence of strong abundance gradient in the ISM in NGC 4636 and reveals that both $\alpha$ elements and Fe equally show the abundance gradient. Their ratio is close to the solar value at all radii. The absolute values of the abundances are higher than those derived in Mushotzky et al. (1994), who assumed a solar ratio in the metals, but the temperatures and hydrogen column densities are consistent.

4. DISCUSSION

By carefully examining the abundance ratios and uncertainties in the Fe-L complex, we have concluded that the ISM abundances of Fe and $\alpha$ elements in the X-ray luminous galaxy, NGC 4636, are in fact as high as about 1 solar within $r < 4'$. The abundance ratio between $A_{\alpha}$ and $A_{\text{Fe}}$ is very close to the solar ratio within ~20%. This means that both Type Ia and Type II SN ejecta make significant contribution in the ISM.

The ISM iron abundance is expected to be given by

$$Z_{\text{Fe,ISM}} = (Z_{\text{Fe}}^{\odot}) + 5 \theta_{\text{SNII}} \left( \frac{M_{\text{Fe}}^{\odot}}{0.7 M_{\odot}} \right) h_{50}^2$$

(Loewenstein & Mathews 1991; Renzini et al. 1993), where $(Z_{\text{Fe}}^{\odot})$ is the average iron abundance of the stars in units of the solar abundance, $h_{50} = H_0/50$ the Hubble constant in units of 50 km s$^{-1}$ Mpc$^{-1}$, $\theta_{\text{SNII}}$ is the present rate of Type Ia SNe in ellipticals in units of the rate as estimated by Tammann (1982), and $M_{\text{Fe}}^{\odot}$ is the iron yield per Type Ia SN event. The stellar Fe abundance, $(Z_{\text{Fe}}^{\odot})$, averaged over the whole galaxy is 0.74 solar (Arimoto et al. 1997). Since our revised value of $A_{\text{Fe}}$ is fairly close to these stellar values, the previously quoted severe problem that the ISM abundance was lower than the stellar metallicity has been mostly removed.

We can solve for the relative contribution from Type Ia and II SNe on $\alpha$ elements and Fe. If we assume that Type II SN products have 3 times higher value of $A_{\alpha}$ than $A_{\text{Fe}}$ (Thielemann et al. 1996) and Type Ia SNe produce only Fe, the Type II SN

![Graph showing abundance gradient and metal distribution in the ISM of NGC 4636.]
contribution necessary to produce the observed $A_\alpha$ (1 solar) can enrich Fe to $A_{\text{Fe}} = 1/3$ solar. The rest of $A_{\text{Fe}}$, i.e., 2/3 of the best-fit Fe abundance, has to be explained by Type Ia SNe. Using equation (1), we can estimate the Type Ia SN rate $\dot{N}_{\text{SN Ia}}$. In order to derive an upper limit for $\dot{N}_{\text{SN Ia}}$, let us assume that stars contain no Fe from Type Ia SNe. This gives an equation only for the Type Ia SN contribution, $Z_{\text{ISM,SN Ia}}^{\text{Fe}} > 5\dot{N}_{\text{SN Ia}} (M_{\odot}/0.7 M_{\odot}) h_{50}^2$. The left-hand side is now estimated to be $\sim 0.7$ solar, so that the condition for $\dot{N}_{\text{SN Ia}}$ is $\dot{N}_{\text{SN Ia}} h_{50}^2 < 0.14$. Therefore, the present abundance result suggests that Type Ia SN rate would be less than 1/7 of Tammann’s rate for $h_{50} = 1$. Considering the uncertainties in $A_\alpha$ and $A_{\text{Fe}}$, this is consistent with the recent estimation of $\dot{N}_{\text{SN Ia}} \sim 1/4$ by Cappellaro et al. (1993) based on the supernova counting.

A systematic study of the ISM abundance involving many galaxies would be necessary to further look into this problem. Also, Fe-L diagnostics need to be closely examined in order to reach consistent answers among the models (Arimoto et al. 1997).

We have confirmed and refined the strong abundance gradient feature in the ISM discovered by Mushotzky et al. (1994). In addition, we have for the first time discovered strong abundance gradient in $\alpha$ elements, which is very similar to that of $A_{\text{Fe}}$. There may be an internal metallicity gradient in the ISM within the galaxy, as suggested from the significant gradient in the stellar metallicity within $r_e$ (Davies, Sadler, & Peletier 1993). However, no information is available about the stellar metallicity in larger scales. There exists an extended X-ray emission around NGC 4636 with a radius of more than 100 kpc, as discovered by Trinchieri et al. (1994) and confirmed with ASCA by Matsushita (1997). Since the hot gas responsible for the extended emission has a very low metallicity as seen in the data in $r = 8''-12''$, the abundance gradient can be explained in terms of the growing contribution from the metal-poor gas in the outer region. The similarity in the slope of $A_{\alpha}$ and $A_{\text{Fe}}$ gradient suggests common dilution due to external gas.

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