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The Abundance Pattern in the Hot ISM of NGC 4472: Insights and Anomalies

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ABSTRACT

Important clues to the chemical and dynamical history of elliptical galaxies are encoded in the abundances of heavy elements in the X-ray emitting plasma. We derive the hot ISM abundance pattern in inner ($0-2.3R_e$) and outer ($2.3-4.6R_e$) regions of NGC 4472 from analysis of *Suzaku* spectra, supported by analysis of co-spatial *XMM-Newton* spectra. The low background and relatively sharp spectral resolution of the *Suzaku* XIS detectors, combined with the high luminosity and temperature in NGC 4472, enable us to derive a particularly extensive abundance pattern that encompasses O, Ne, Mg, Al, Si, S, Ar, Ca, Fe, and Ni in both regions. We apply simple chemical evolution models to these data, and conclude that the abundances are best explained by a combination of α -element enhanced stellar mass loss and direct injection of Type Ia supernova (SNIa) ejecta. We thus confirm the inference, based on optical data, that the stars in elliptical galaxies have supersolar $[\alpha/Fe]$ ratios, but find that the present-day SNIa rate is $\sim 4-6$ times lower than the standard value. We find SNIa yield sets that reproduce Ca and Ar, or Ni, but not all three simultaneously. The low abundance of O relative to Ne and Mg implies that standard core collapse nucleosynthesis models overproduce O by ~ 2 .

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1. Introduction

1.1. Context

Galaxy formation encompasses the processes of star formation and largescale dynamics – where dynamics is defined in its broadest sense to include the assembly of dark matter and baryons, as well as the exchange of mass and energy among the various galactic components and with the external environment. Star formation ultimately leads to the nuclear production of metals, while dynamical processes determine their destination. Therefore the abundance, abundance pattern, and location of metals in different galaxies in the *local* universe provide fundamental insights into the construction and development of galaxies..

Chemical evolution modeling quantifies this connection. Heavy elements are both statically and explosively synthesized in evolving stars following episodes of star formation with abundances that reflects the total mass of stars formed and the initial mass function (IMF), as well as the production rate of Type Ia supernova (SNIa) progenitor binary stars. These metals are subsequently returned to the interstellar medium (ISM), and the enriched ISM may regenerate stars or escape into intergalactic space, depending on the level of supernova energy injection that accompanies the metal enrichment – and how efficiently that energy is channeled into outflow. These processes must depend on initial conditions and environment in such a way as to produce the diverse and evolving universe of galaxies that we observe from the Local Group out to the distant universe at redshifts of 6 and greater. One can illuminate the history in the ensemble of galaxies in a cluster by measuring abundances in the intracluster medium (ICM; see, e.g., Loewenstein 2006), and in individual galaxies by measuring stellar and interstellar abundances.

It is evident that in giant elliptical galaxies, predominantly composed of stellar populations passively evolving since the early universe, the star-gas cycle was greatly accelerated and concentrated in time relative to the Milky Way and other late-type galaxies (Papovich et al. 2006; van Dokkum & van der Marel 2007; Jimenez et al. 2007; Perez-Gonzalez et al. 2008). Moreover, the prodigious metal content in the intergalactic medium of galaxy clusters dominated by ellipticals implies that strong galactic winds were driven in these galaxies. However, details such as the precise initial epoch and duration of star formation, the form of the IMF, the relative roles of SNIa and core collapse (SNII) supernovae in enriching and expelling ISM – and how all these depend on mass and environment – remain unclear.

Abundances in the stellar component and their correlation with structural parameters, provide key diagnostics of elliptical galaxy ages, star formation and accretion histories, and IMFs (Thomas et al. 2005; Pipino et al. 2009; Clemens et al. 2009; Colavitti, Pipino, & Matteucci 2009; Trager & Somerville 2009; Recchi et al. 2009). Since stars dominate the baryon content of ellipticals, the level of stellar α -element enrichment is determined by the past integrated frequency of SNII, and hence the number of massive stars formed. For a given total mass in stars, this then constrains the IMF. The stellar α/Fe ratio is then determined by the relative contributions of SNIa and SNII. Careful modeling of multiband photometry and very high signal-to-noise optical spectroscopy can, in principle, determine the abundances as well as the ages of ellipticals. However, since interpretation of colors and absorption line indices suffer from a degeneracy in their dependence on the SFH and overall metallicity – even for an assumed IMF and distribution of abundance ratios (Howell 2005) – optical studies of the composite stellar population cannot clearly and unambiguously measure these fundamental quantities. The additional consideration of Balmer emission line indices can assist in breaking some of the degeneracies (Trager et al. 2000) but, e.g., does not easily distinguish a very old stellar population with a “frosting” of recent star formation episodes from a somewhat younger one (Serra & Trager 2007; Trager & Somerville 2009). Since, optical line indices can only be interpreted within the context of a conjectured SFH and IMF, they are more robust in providing consistency tests of combinations of ages and abundance ratios (*i.e.*, Mg/Fe) than they are in determining absolute abundances (Howell 2005). Moreover, the effects of variations in individual elements is not easily disentangled (Lee et al. 2009), and optical absorption features are only measured out to 1-2 (projected) effective radii (R_e) – the abundances in, typically, half of the stellar mass are unknown.

Fortunately, mass lost by post-main-sequence stars in elliptical galaxies is heated to millions of degrees K as it is incorporated into the interstellar medium (ISM), where it is amenable to relatively robust and straightforward X-ray spectroscopic analysis (Mathews & Brighenti 2003). Because the gas, with the possible exception of a few high oscillator strength lines, is optically thin the absolute abundances of a wide range of elements with prominent emission features that can include C, N, O, Ne, Mg, Al, Si, S, Ar, Ca, Fe, and Ni may be directly derived given sufficient spectral resolution, sensitivity, and bandpass. Because this approach relies on strong emission lines, X-ray derived abundances may be determined out to very large radii – often extending to the edge of the optical galaxy and beyond (Matsushita et al. 1998).

While hot ISM abundances may be more directly derived than stellar abundances, their interpretation requires careful deconstruction within the context of physical gasdynamical and chemical evolutionary models. Unlike the case of the ICM that dominates the baryon content in clusters, most of the metals produced by the evolving stellar population are

expelled from galaxies or locked up in stars – not accumulated in a reservoir of hot gas. Enrichment timescales for elements synthesized by SNIa, SNII, and intermediate mass stars are distinct, and coupled in a complex way to star formation, mass return, and outflow timescales. Nevertheless, one can employ reasonable assumptions, approximations, and simplifications to construct simple models that track the evolution of global abundances of these elements. Comparison of these models with observations constrain important features of the nature of the galaxy stellar population, as well as the rate and ultimate disposition of metals ejected as this population evolves. As such, they may serve as guides to subsequent more complex modeling.

In this paper, we introduce such models and apply them to the hot ISM abundances in NGC 4472 that we infer from analysis of *Suzaku* and *XMM-Newton* spectra. Because of its brightness and temperature structure, a particularly well-determined and wide-ranging X-ray abundance pattern is measurable in NGC 4472 – one that is made more accessible utilizing the low internal background and sharp energy resolution of the *Suzaku* XIS detectors.

1.2. Brief Survey of Previous X-ray Results

High quality X-ray spectra for a large sample of elliptical galaxies was first obtained with the *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*). Fe abundances in most of the X-ray brightest ellipticals were found to be within a factor of two of solar, with no strong evidence of non-solar ratios of α -elements to Fe (Buote & Fabian 1998; Matsushita, Ohashi, & Makishima 2001). X-ray spectra extracted from the *Chandra* and *XMM-Newton* CCD detectors take advantage of improved sensitivity and spectral resolution, and far superior angular resolution, to more cleanly derive abundance patterns and gradients (Humphrey & Buote 2006, and references therein). *Chandra* results indicate that ISM Fe abundances are roughly solar and decline slowly with radius as far out as tens of kpc (Humphrey & Buote 2006; Athey 2007). In addition, approximately solar Mg/Fe and Si/Fe ratios and subsolar O/Fe ratios are inferred.

Abundances derived from the *XMM-Newton* reflection grating spectrometer (RGS) benefit from cleaner separation of individual features, so that effects of resonance scattering on optically thick lines, and multiphase gas on temperature-sensitive lines and line ratios, may be directly addressed. Analysis of *XMM-Newton* reflection grating spectrometer (RGS) spectra of NGC 4636 by Xu et al. (2002) yields subsolar Mg/Fe and O/Fe ratios, a roughly solar Ne/Fe ratio, and a supersolar N/Fe ratio. The difficulty in analyzing grating spectra of extended sources, and limitations in sensitivity and bandpass, restrict the applicability of RGS spectroscopy to X-ray luminous galaxies with the highest central X-ray surface brightnesses.

Ji et al. (2009) analyze *Chandra* and *XMM-Newton* EPIC and RGS data in 10 bright systems. They confirm the above abundance pattern with respect to O/Mg/Si/Fe, and extend to Ne and S that show no strong deviations from solar ratios, and Ni that is generally supersolar.

The lower internal background and sharper energy resolution of the *Suzaku* XIS CCDs enable the derivation of abundance patterns to larger radii, and allow for a more accurate measurement of possible features at high energy originating from S, Ar, Ca, and Ni. The *Suzaku* low energy sensitivity makes it suitable for measuring O as well. Results on NGC 1399 (Matsushita et al. 2007), NGC 720 (Tawara et al. 2008), NGC 5044 (Komiya et al. 2009), NGC 507 (Sato et al. 2009), and NGC 4636 (Hayashi et al. 2009) confirm the solar Si/Fe and subsolar O/Fe ratios, demonstrate that these persist to large radii, and extend this behavior to S/Fe. It is the case that this is also broadly true of Mg/Fe; however, Mg/Fe is somewhat lower in NGC 720 and NGC 1399. Ne/Fe seemingly shows more variation, coming in at solar in NGC 4636, subsolar in NGC 720 and supersolar in NGC 507 and NGC 5044. Ne does not seem to trace O as might be expected.

Optical spectra imply that the stellar ratio of α elements to Fe, expressed logarithmically with respect to solar as $[\alpha/Fe]$, is such that $[\alpha/Fe] \sim 0.3 - 0.5$ – although there is little known about this ratio well beyond R_e or about the relative abundances of different α elements. If stellar mass loss dominates ISM enrichment, they should display the same α -element overabundance. Based on the the above summary, this is clearly not the case. Direct injection of SNIa will skew that abundance pattern towards lower $[\alpha/Fe]$, but should do so in a way that does not effect relative abundances of elements with low SNIa nucleosynthetic yields such as O, Ne, and Mg. The ratios, with respect to Fe, of Si, S, Ar, and Ca may be less affected, depending on the level of SNIa enrichment since these elements are produced with moderate efficiency by SNIa. The solar ratio seen for most of the α elements in the hot ISM indicates a significant role for SNIa enrichment; but, the fact that O is particularly underabundant while Mg and Ne are as abundant as Si and S does not comfortably fit into this scheme. We examine these issues more quantitatively below with respect to the ISM abundances in NGC 4472, where measurements of Ca and Ar in the ISM add a new twist to attempts to understand the enrichment of this galaxy.

2. Construction of NGC 4472 Spectra and Associated Files

2.1. *Suzaku* Spectral Extraction

NGC 4472 was observed with *Suzaku* (Mitsuda et al. 2007) between 2006-12-03 and 2006-12-06 (OBSID=801064010) with an on-source exposure time of 121 ksec – 94 (27)

ksec in 3×3 (5×5) CCD editing mode. At the time of observation, three co-aligned, $17.8' \times 17.8'$ field-of-view X-ray Imaging Spectrometer (XIS) CCD cameras (Koyama et al. 2007) – two front-illuminated (FI: XIS0 and XIS3) and one back-illuminated (BI:XIS1) – were operational, each XIS in the focal plane of an X-ray Telescope (XRT) with a $2'$ half-power diameter (Serlemitsos et al. 2007).

Observations were conducted utilizing the space-row charge injection (SCI) technique that reverses the degradation in energy resolution caused by accumulated radiation damage (Nakajima et al. 2008). We initiate our data reduction with the unfiltered event files. These data underwent Version 2.0.6.13 pipeline processing on 2007-08-18 that enables one to properly account for the effect of SCI on instrument characteristics and performance (Uchiyama et al. 2008). We reprocess the unfiltered event files by hand in order to apply updated calibration data and software. Our analysis generally follows the procedures outlined in “The Suzaku Data Reduction Guide”¹, as implemented in HEASoft version 6.5.1². We recalculate PI values and grades, select event grades (0, 2, 3, 4, 6) that correspond to X-ray photon events, filter on pixel status (eliminating bad charge transfer efficiency columns, and rows invalidated by the charge injection process) and select good time intervals (GTI) based on pointing, data and telemetry rates, SAA proximity (“SAA_HXD \equiv 0, T_SAA_HXD $>$ 436”), and proximity to the earth’s limb and illuminated Earth (“ELV $>$ 5, DYE_ELV $>$ 20”). In addition, telemetry-saturated frames and calibration source photons are screened out; and, hot and flickering pixels are removed. Finally, we accept only GTI where the revised geomagnetic cut-off rigidity COR2 $>$ 4, thus eliminating intervals with the highest particle background level (Tawa et al. 2008) without compromising overall statistical accuracy (experiments with the stricter criteria COR2 $>$ 6 yields identical results). 5×5 event files are converted to 3×3 mode format, and merged with the 3×3 event files.

Spectra are extracted from $0 - 4'$ ($0 - 2.3R_e$) circular (inner) and $4 - 8'$ ($2.3 - 4.6R_e$) annular (outer) regions, centered on the NGC 4472 optical nucleus ($\alpha = 12\ 29\ 46.7$, $\delta = +08\ 00\ 02$) that very closely corresponds to the X-ray peak in the *Suzaku* image. Relatively large regions are chosen to minimize PSF effects, and maximize the accuracy and range of abundance measurements.

The spectral redistribution matrix files (**rmf**) are generated using **xisrmfgen** version 2009-02-28. The **rmf** and spectral files are binned to 2048 channels. The effective area function files (**arf**) for the source spectra are generated by the **xissimarfgen** version 2009-01-08 Monte Carlo ray-tracing program (Ishisaki et al. 2007) with 400000 simulation photons per

¹<http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/abc/>

²<http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/>

energy bin, and an input source fits image file generated from a β -model fit to the background-subtracted X-ray surface brightness profile extracted from archival *Chandra* data. Spectra from the FI chips, XIS0 and XIS3, are co-added and a weighted XIS0+3 response functions calculated from their respective **rmf** and **arf** files. Source spectra are grouped into bins with a minimum of 15 cts. Best-fit parameters and parameter uncertainties are derived using χ^2 statistics; experiments with the Cash statistic yielded very similar results.

The XIS background includes contributions from Non-X-ray (charged particle) Background (NXB), Galactic X-ray Background (GXB), and (extragalactic) Cosmic X-ray Background (CXB). Since NGC 4472 fills the *Suzaku* field of view, we estimate and subtract the NXB component and include an additional thermal component in our spectral fits to account for the GXB. The CXB has a similar shape, but a much smaller magnitude, than the intrinsic flux from low-mass X-ray binaries (LMXBs) and is subsumed into that spectral component. The NXB component is estimated from observations of the night earth taken in SCI mode within 150 days of the starting or ending dates of our observation using **xisnxbgen** version 2008-03-08. The NXB event list in that time interval undergoes the identical screening as the source data, is sorted by geomagnetic cut-off rigidity, and weighted according to the cut-off rigidity distribution in the source event file (Tawa et al. 2008). The estimated NXB spectra include only those events collected in the regions on the detector from which the source spectra are extracted. Since the NXB has a spatial distribution distinct from that of the NGC 4472 X-ray emission, a separate **arf** file is generated using 2000000 simulation photons per energy bin from a uniform source of radius 20' and applied to the background in spectral fits. Combined XIS0+3 NXB spectra and response functions are constructed as described above for the source spectra.

The effective exposure time of the XIS0+3 (XIS1) spectrum is 232 ks (117 ks). The total 0.3-12 keV band counts are 132032 (inner) and 70286 (outer) for XIS0+3, and 107232 (inner) and 72758 (outer) for XIS1. The fraction of the total count rate in the NXB is 1.4% (inner) and 8.3% (outer) for XIS0+3, and 1.8% (inner) and 10.3% (outer) for XIS1. Even in the outer region, its contribution is small in the region where spectral features of interest lie (see Figure 3, below).

2.2. *XMM-Newton* Spectral Extraction

NGC 4472 was observed for ~ 90 ksec with *XMM-Newton*. After cleaning the dataset (the last 20 ksec of the full-field light curve showed significant flares), ~ 81 ksec (~ 72 ksec) of useful observation time remained for the EPIC MOS1 and MOS2 (pn) detectors. The data were reduced and extracted using SAS 6.5.0. The latest calibration products were used

to determine the response files for the spectral analysis. The extracted spectra are binned so that each channel has a minimum of 20 counts, and we consider energy ranges of 0.4–7.0 keV and 0.32–2.0 keV for the EPIC cameras and RGS detectors, respectively. To account for the fact that NGC 4472 is an extended source, we used the `rgsxsrmc` model in XSPEC 11, extracting the *Chandra* ACIS-S image to create a surface brightness distribution model to convolve with the RGS response. The background for the central region was taken from the blank sky background files provided by the *XMM-Newton* Science Center. These were scaled to match the EPIC and RGS high energy continua. EPIC MOS1, MOS2, and pn spectra are extracted from the inner and outer regions described above. Subdividing the inner region ($r < 200''$) into multiple annular regions, and fitting the corresponding EPIC spectra, reveals no significant \sim arcminute gradients in abundance ratios (Section 3.2)

3. Spectral Analysis

3.1. *Suzaku* Spectral Analysis

The NGC 4472 *Suzaku* XIS0+3 and XIS1 spectra are simultaneously fit in the 0.45–7.0 keV band using XSPEC 12.5 with a source model consisting of a two-temperature thermal plasma (**vapec**) model with a single set of heavy element abundances (C, N, O, Ne, Mg, Al, Si, S, Ar, Ca, Fe, Ni), plus a 7 keV thermal bremsstrahlung component to account for the LMXBs (and the relatively insignificant emission from the CXB and, for the inner region, any activity associated with the dormant supermassive black hole; see Loewenstein et al. 2001). The absorption is fixed at the Galactic column density of $1.65 \times 10^{20} \text{ cm}^{-2}$ (Dickey & Lockman 1990). When free to vary, the bremsstrahlung temperature and column density are found to be consistent with these values; and, the **vapec** parameters essentially unchanged. This is also the case if a power-law model is adopted to characterize the LMXBs. The bremsstrahlung flux is consistent with previous estimates of the LMXB contribution (Athey 2007). The Si K-edge region (1.82–1.841 keV) was excluded from the spectra, although this had negligible effect on the final fits aside from a small reduction in χ^2 . A constant XIS1/XIS0+3 multiplicative factor is included and generally ranges from 1.01–1.05. The Grevesse & Sauval (1998) solar abundance standard is adopted. C emission lines are outside of the *Suzaku* bandpass, so the C abundance is fixed at solar. The inner and outer regions are separately fitted. The outer spectrum requires an additional cooler component, presumably from GXB emission that we model by a single temperature thermal plasma model with all abundances except N and O fixed at solar (allowing other elements to vary, or adding a second temperature component did not improve fits or affect hot ISM parameters of interest). Because the GXB is more prominent there, the outer spectra are used to determine the GXB

parameters (except for the normalization) that are then fixed in analyzing the inner spectra. The relative fluxes of the GXB component in the inner and outer regions are consistent with the ratio of their projected areas, and the overall GXB surface brightness, temperature (0.15 ± 0.04 keV), and oxygen abundance (0.15, 0.11-0.29 at 90% confidence) are consistent with what was found in the source-free Ursa Minor Dwarf Spheroidal Field (Loewenstein, Kusenko, & Biermann 2009) – there is no evidence that any of the “GXB” constitutes an intrinsic NGC 4472 cool component. Fits to the inner spectra require two ISM temperature components. The temperatures we find in the inner region are 0.798 ± 0.004 and 1.42 ± 0.05 keV. The outer region may be fitted with a single-temperature (1.2 keV) model (reduced $\chi^2 = 1.05$), but is better fitted ($\Delta\chi^2 = 96$) with a two-temperature (0.93 ± 0.08 and 1.55 ± 0.10 keV) model. These are consistent with the temperature structure we derive from spectra extracted over a finer series of annuli (see next section). The best-fit N abundances are 0 with upper limits of 0.75 (0.6) solar in spectral fits to the inner (outer) spectra, and are fixed in the final fits. The addition of a third ISM temperature component did not significantly affect the best-fit abundances.

Spectra and best-fit models, are displayed in detail in Figures 1-4. The best fit abundances and 90% ($\Delta\chi^2 = 2.7$) confidence limits are shown in Table 1. The best-fit abundance ratios, with respect to Fe, for the inner and outer *Suzaku* spectra are compared in Figure 5.

3.2. *XMM-Newton Spectral Analysis and Comparison to with Suzaku*

Spectral analysis of the *XMM-Newton* EPIC MOS1+2 and pn data in the same extraction regions yielded best fits that are generally consistent with the above, though with some discrepancies (Table 1, Figure 6). Although blank sky background is subtracted from these spectra, an additional small GXB component is included. The best-fit normalization is $3 - 10\times$ lower than in the (non-GXB-subtracted) *Suzaku* spectra. The effect of this addition is to improve the spectral fits ($\Delta\chi^2 = 53$ for the MOS, 16 for the pn) and increase the parameter uncertainties.

There are substantial differences in the derived best-fit abundances of Ar, Ca, and Ni derived from EPIC and *Suzaku* spectra (Figure 6a); but, the errors are large (particularly for the former) and the 90% confidence ranges overlap. The most serious discrepancies are the low outer-region Mg abundance and inner-region O abundance derived from EPIC spectra.

The *Suzaku* abundance pattern we derive in the inner region is in very good accord with that found by Ji et al. (2009) from analysis of EPIC and RGS data, and from our own RGS analysis (Figure 6a, Table 1). Although the latter samples a smaller region, the

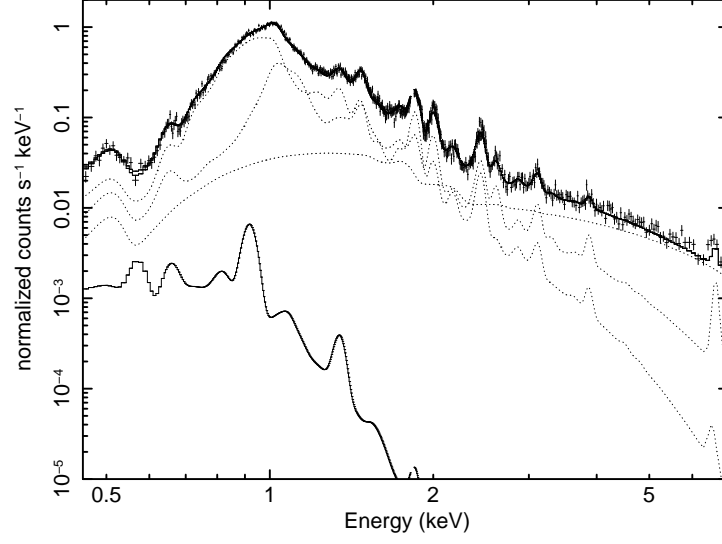
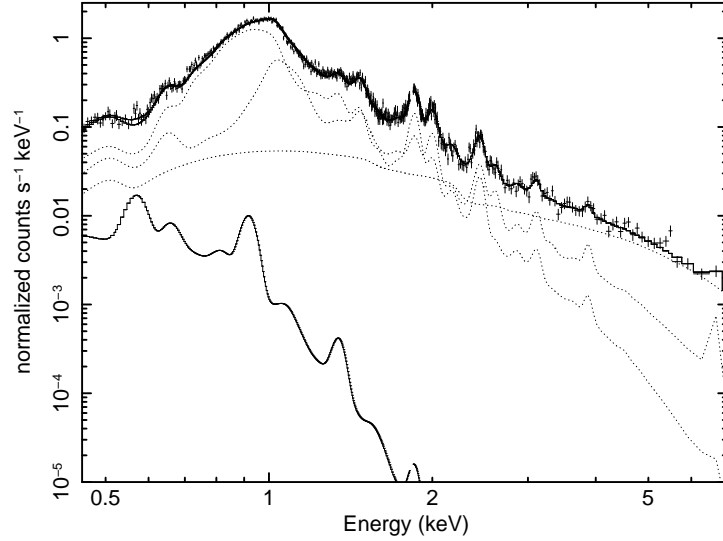


Fig. 1.— **top (a)**: XIS0+3 inner region spectrum and best-fit model. Also shown are the separate components (from lowest to highest at 1 keV: GXB, thermal bremsstrahlung LMXB, hotter and cooler thermal plasma components of the hot ISM). **bottom (b)**: Same for XIS1.



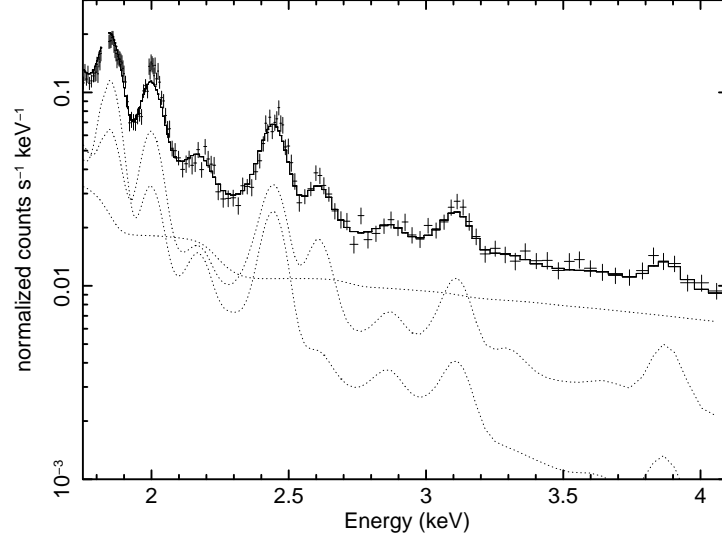
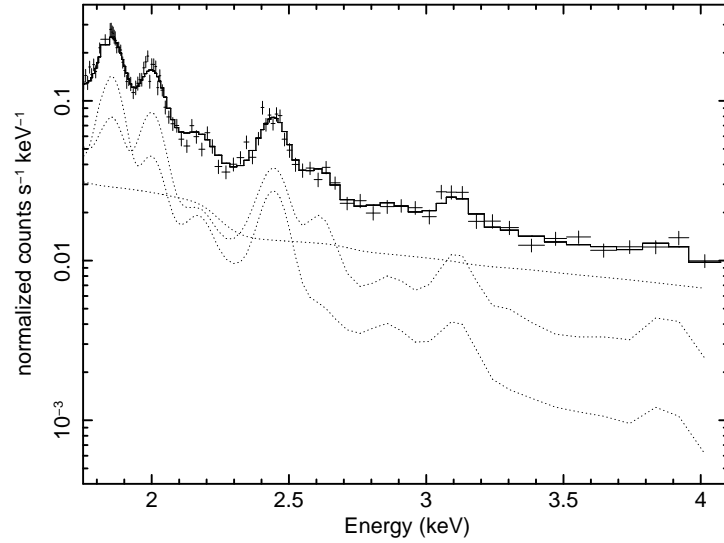


Fig. 2.— Same as Figure 1, zoomed to the Si/S/Ar/Ca spectral region. Prominent features from left to right predominantly originate in the following ions: Si XIII ($K\alpha$), Si XIV ($K\alpha$), SiXII ($K\beta$), SXV ($K\alpha$), SXVI ($K\alpha$), SXV ($K\beta$), Ar XVII ($K\alpha$), CaXIX ($K\alpha$).



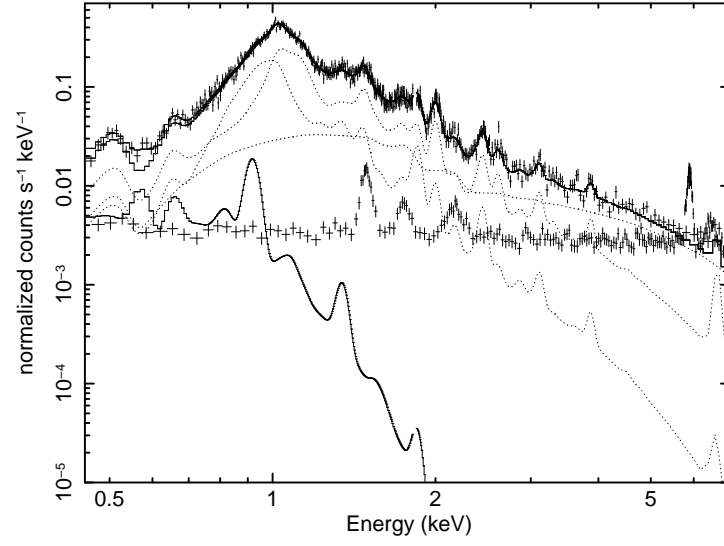
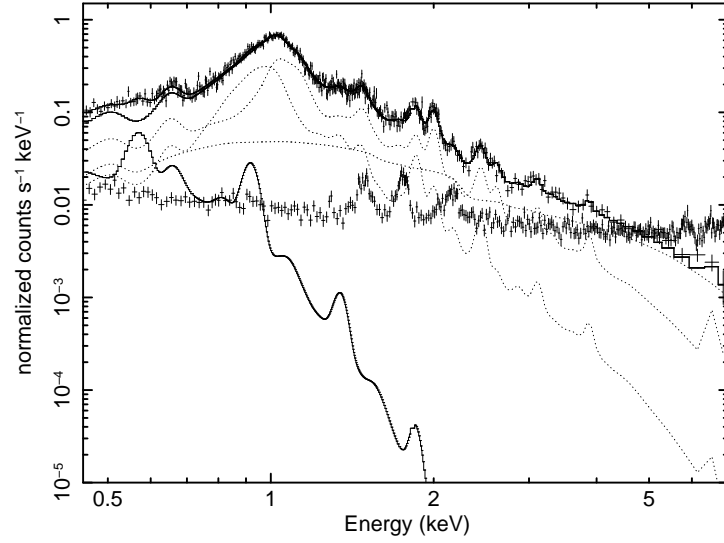


Fig. 3.— Same as Figure 1 for outer region spectra, with NXB contribution now included.



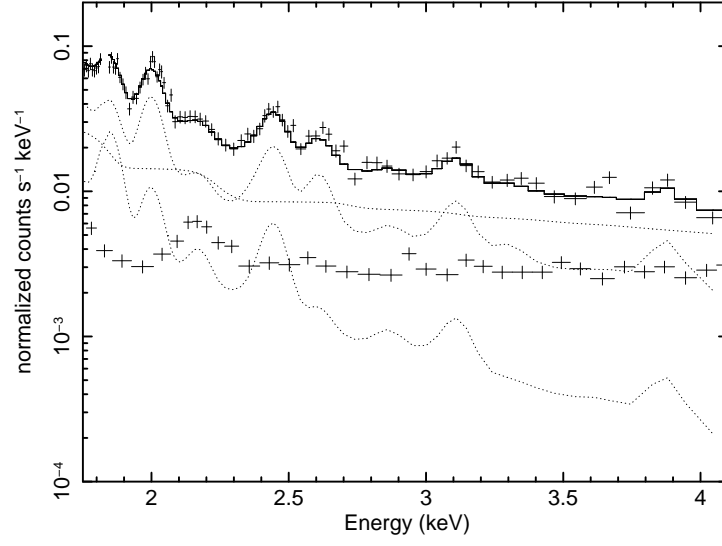
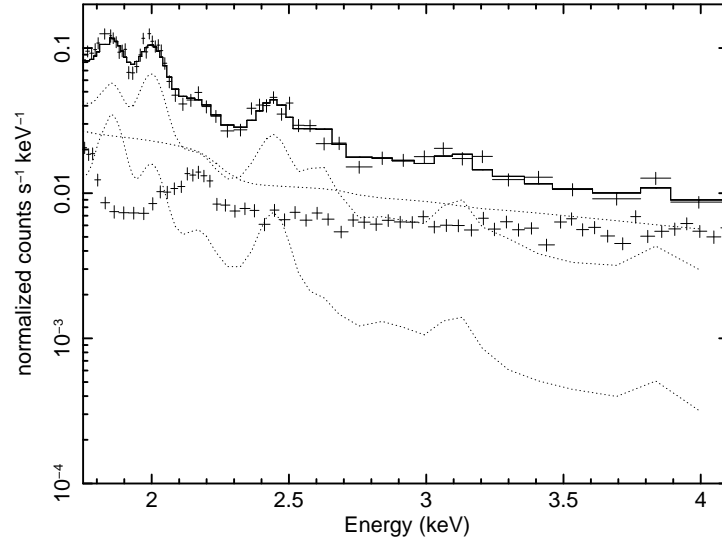


Fig. 4.— Si/S/Ar/Ca spectral region as in Figure 2 for outer spatial region.



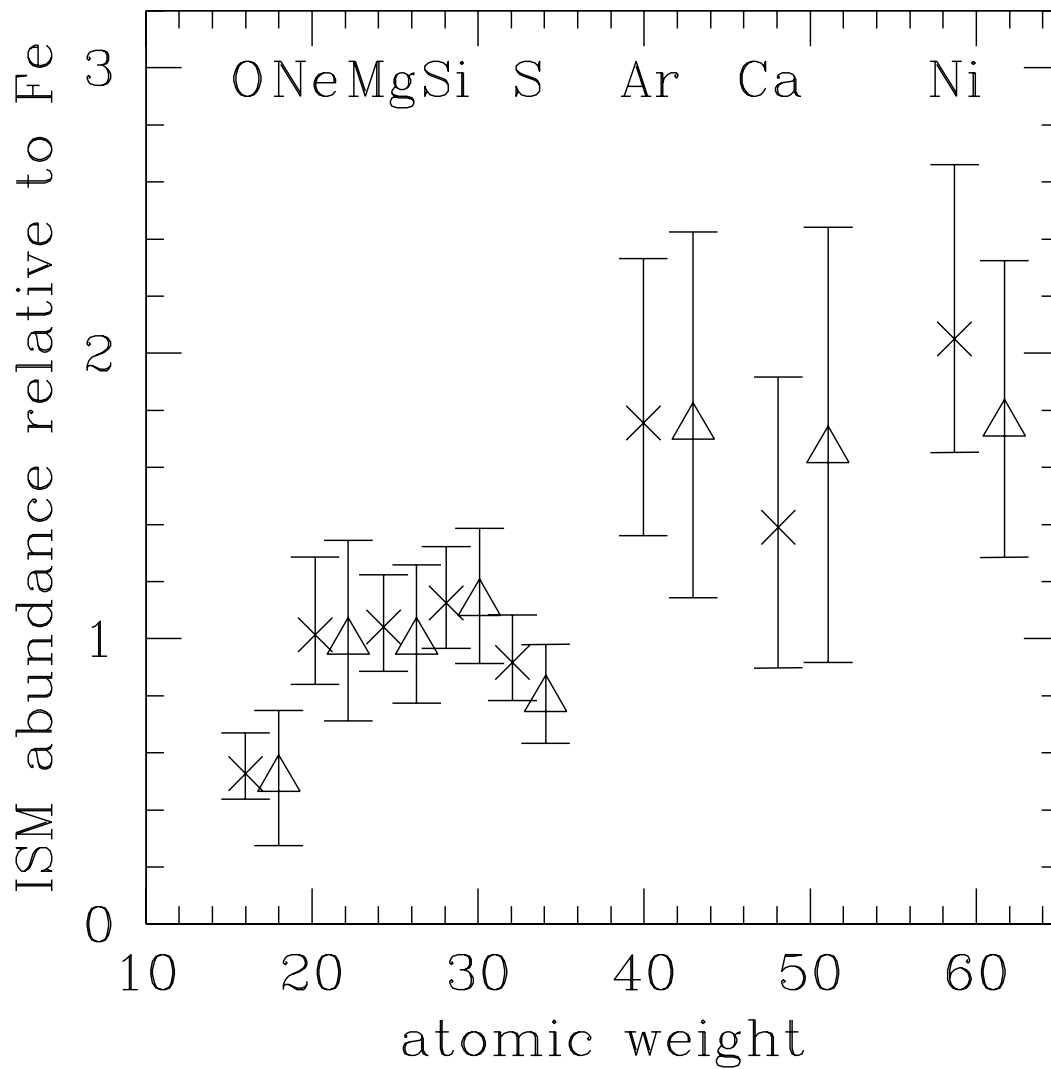


Fig. 5.— Inner (crosses), and outer (open triangles, offset to right) *Suzaku* abundance patterns. Ca is shifted to the right.

best-fit temperatures and abundances are consistent with our analysis of the inner region *Suzaku* data except for N (best RGS fit: 3.7 ± 1.7 at 90% confidence) that is sensitive to the treatment of the background, and (marginally) Mg.

The *XMM-Newton* EPIC angular resolution allows us to determine the temperature and abundances in 9 annular rings out to $300''$. In our analysis we find that a two-temperature **vaptec** plasma model is needed for most of the radial bins. This requirement is driven by residuals to one-temperature fits in the CCD spectra near the energy of the Fe XVII line. This is in contrast to the analysis of Nagino & Matsushita (2009), who adopt a one-temperature model in their fits. In our analysis we have used fairly wide annuli ($30''$ minimum) and adjusted their widths to include at least 20000 counts in order to allow us to accurately determine the abundances in each ring. This requirement results in extraction regions that span a larger fraction of the temperature gradient so that two-temperature models are needed to fit the data. Our temperature profile is shown in Figure 7, and shows a positive gradient. The cooler component temperature is about 60% that of the hotter at all radii. The ratio of hot to cool components increases with radius, so that in the outer annuli the hotter component dominates the emission.

Utilizing these same annular extraction regions, we search for abundance gradients on a finer scale than that of the *Suzaku* data for the best-determined abundances: O, Ne, Mg, Si, S, and Fe. We determine the abundance gradient for each element with respect to Fe; and, in general the profile is consistent with a constant. The only ratio that shows a gradient is Mg-to-Fe, which is flat in the inner 150 - 200'' and declines to about half the central value at $\sim 300''$.

In the following sections, we adopt the abundances that we infer from fitting the *Suzaku* spectra for comparison with simple chemical evolution models. We consider these more robust, for the crude spatial binning that we employ, because of the lower background and sharper energy resolution of *Suzaku*. This is illustrated in Figure 8 that compares MOS1, pn, and XIS0 inner region spectra, and Figure 9 that compares pn and XIS0 outer region spectra. The *Suzaku* spectral features, including the 1.0 keV Ne X bump embedded in the Fe-L line complex, the OVII line at 0.65 keV, and the Mg XI and Mg XII lines at 1.35 and 1.47 keV are significantly sharper than their EPIC counterparts (and in some instances sharper than the resolution in the latest *Suzaku* calibration). The reduced high energy background is particularly significant in the Si/S/Ar/Ca spectral regime for the outer region (Figure 8).

We note the formal measurement of a large Al abundance in the inner region (with *XMM-Newton* and *Suzaku*) and the outer regions (*Suzaku* only – there was residual non-X-ray Al fluorescence emission in the outer-region MOS spectra). This would be the first detection of an odd-atomic-number element in the hot ISM of an elliptical galaxy. However,

Table 1. Best Fit ISM Abundances

	χ^2_ν	O	Ne	Mg	Al	Si	S	Ar	Ca	Fe	Ni
S-in	1.13	1.08 ^{0.24} _{0.15}	2.08 ^{0.46} _{0.30}	2.14 ^{0.17} _{0.25}	3.98 ^{1.46} _{0.97}	2.31 ^{0.18} _{0.25}	1.88 ^{0.18} _{0.21}	3.61 ^{1.04} _{0.74}	2.86 ^{0.99} _{0.98}	2.05 ^{0.32} _{0.19}	4.21 ^{1.07} _{0.71}
MOS-in	1.18	0.77 ^{0.54} _{0.42}	1.64 ^{0.43} _{0.32}	2.08 ^{0.27} _{0.29}	7.35 ^{2.10} _{1.50}	2.21 ^{0.40} _{0.17}	1.85 ^{0.27} _{0.20}	2.85 ^{1.05} _{1.04}	2.38 ^{1.54} _{1.53}	2.13 ^{0.31} _{0.19}	4.31 ^{1.13} _{0.83}
pn-in	1.07	0.31 ^{0.32} _{0.29}	1.13 ^{0.38} _{0.33}	1.59 ^{0.17} _{0.28}	4.15 ^{1.63} _{1.30}	2.00 ^{0.32} _{0.16}	1.53 ^{0.20} _{0.18}	1.73 ^{1.16} _{1.05}	0.40 ^{1.84} _{0.40}	1.75 ^{0.21} _{0.13}	6.22 ^{1.57} _{1.21}
EPIC-in	1.18	0 ^{0.27} ₀	1.50 ^{0.24} _{0.22}	1.98 ^{0.17} _{0.16}	6.48 ^{0.83} _{1.29}	2.26 ^{0.18} _{0.15}	1.80 ^{0.13} _{0.18}	2.42 ^{0.80} _{0.80}	0.92 ^{1.10} _{0.92}	2.07 ^{0.16} _{0.18}	5.66 ^{0.64} _{0.86}
RGS	1.16	0.81 ^{0.16} _{0.15}	2.05 ^{0.52} _{1.01}	0.97 ^{0.76} _{0.76}	2.42 ^{0.27} _{0.19}	...
S/E-in	1.20	0.80 ^{0.12} _{0.074}	1.45 ^{0.24} _{0.15}	1.65 ^{0.21} _{0.12}	4.11 ^{0.61} _{0.56}	1.87 ^{0.21} _{0.13}	1.50 ^{0.17} _{0.058}	2.26 ^{0.44} _{0.43}	1.71 ^{0.59} _{0.59}	1.74 ^{0.18} _{0.10}	4.13 ^{0.44} _{0.40}
Suz-out	0.99	0.75 ^{0.33} _{0.33}	1.45 ^{0.47} _{0.36}	1.45 ^{0.32} _{0.26}	2.41 ^{1.52} _{1.30}	1.65 ^{0.29} _{0.23}	1.16 ^{0.21} _{0.17}	2.56 ^{0.92} _{0.82}	2.44 ^{1.08} _{1.05}	1.47 ^{0.23} _{0.19}	2.58 ^{0.73} _{0.60}
MOS-out	1.07	1.32 ^{0.87} _{0.59}	1.12 ^{1.24} _{1.07}	0.59 ^{0.76} _{0.59}	...	1.79 ^{0.67} _{0.44}	1.49 ^{0.64} _{0.47}	4.42 ^{3.90} _{3.38}	6.22 ^{5.64} _{5.08}	1.55 ^{0.56} _{0.38}	0.97 ^{1.64} _{0.97}
pn-out	1.04	0.30 ^{0.56} _{0.30}	0 ^{1.35} ₀	0 ^{0.33} ₀	...	1.07 ^{0.51} _{0.32}	1.01 ^{0.44} _{0.34}	1.89 ^{3.11} _{1.89}	2.23 ^{4.47} _{2.23}	1.22 ^{0.63} _{0.37}	1.67 ^{1.71} _{0.68}
EPIC-out	1.06	0.58 ^{0.45} _{0.30}	0.58 ^{0.82} _{0.58}	0.11 ^{0.36} _{0.11}	...	1.28 ^{0.38} _{0.23}	1.13 ^{0.30} _{0.28}	3.04 ^{2.10} _{2.05}	3.57 ^{3.08} _{3.04}	1.27 ^{0.40} _{0.23}	1.16 ^{1.01} _{0.86}
S/E-out	1.02	0.85 ^{0.23} _{0.19}	1.50 ^{0.44} _{0.38}	1.45 ^{0.30} _{0.24}	...	1.74 ^{0.27} _{0.22}	1.25 ^{0.21} _{0.17}	2.73 ^{0.90} _{0.82}	2.54 ^{1.06} _{1.04}	1.56 ^{0.22} _{0.18}	2.63 ^{0.69} _{0.53}

Note. — Reduced χ^2 and best fit abundances relative to the Grevesse & Sauval (1998) solar standard, as well as 90% confidence uncertainties for the inner region *Suzaku* (XIS0+3 and XIS1) spectra (**Suz-in**), outer region *Suzaku* spectra (**Suz-out**), the inner and outer region MOS1+2 and pn spectra (**MOS-in**, **MOS-out**, **pn-in**, **pn-out**), the RGS-1&2 spectra (**RGS**), and the joint fits to EPIC and XIS-plus-EPIC spectra (**EPIC-in**, **EPIC-out**, **S/E-in**, **S/E-out**).

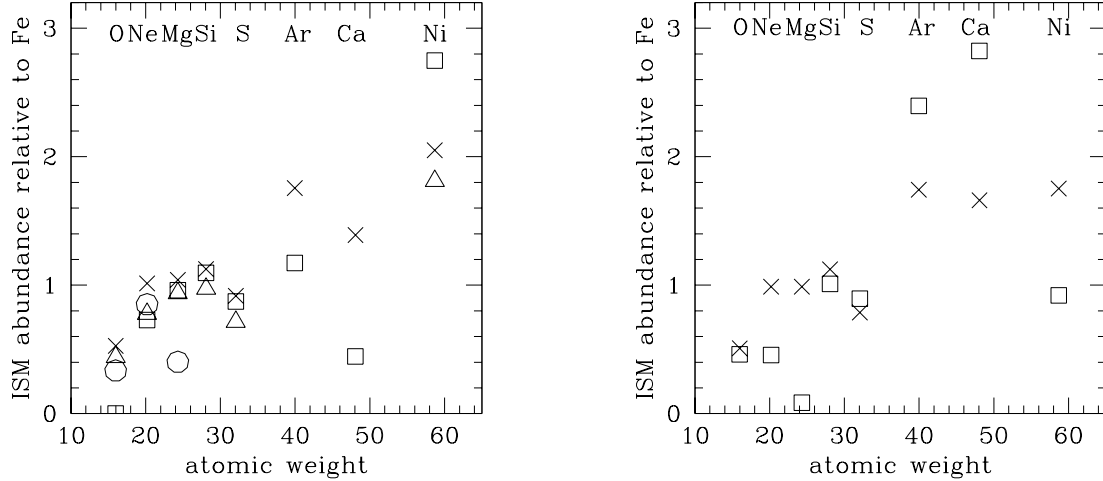


Fig. 6.— **left (a):** Inner region abundance pattern (normalized to Fe) derived from *Suzaku* XIS0+3 and XIS1 (crosses), *XMM-Newton* EPIC from our analysis (open squares) and from Ji et al. (2009) (open triangles), and *XMM-Newton* RGS (open polygons). **right (b):** Outer region abundance pattern (normalized to Fe) derived from *Suzaku* XIS0+3 and XIS1 (crosses), and *XMM-Newton* EPIC (open squares).

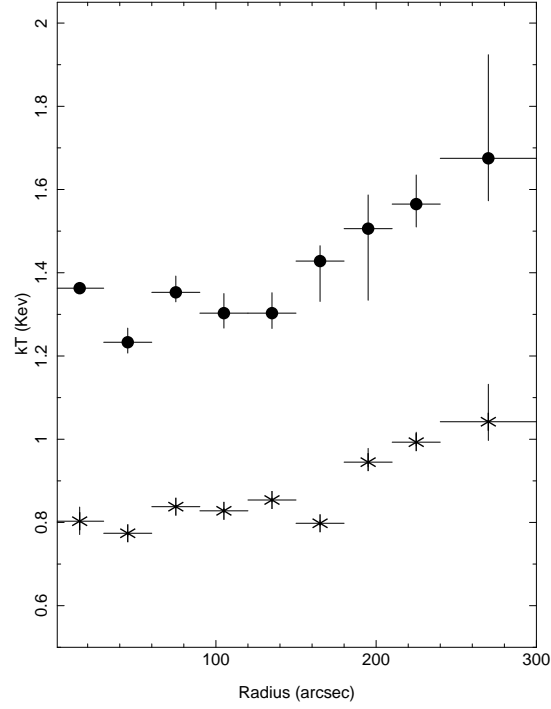


Fig. 7.— The projected temperature profile for N4472 from the center out to 300". The crosses denote the low temperature component, and the filled circles the hotter component. The error bars show the 90% confidence range. The horizontal bars denotes the radial range over which the ISM spectral parameters were derived.

the inferred 1.6 keV Al XI and 1.7 keV Al XII features are weak, and possibly sensitive to uncertainties in the characterization of the continuum in their vicinity. We do not include Al abundances in the model constraints discussed in the subsequent sections, but do display them in comparisons of models with data.

4. Interpreting the NGC 4472 Abundance Pattern

Our method of interpretation, described in more technical detail in Appendix A, may be summarized as follows. We assume that the ISM abundances are determined following the cessation of the main era of star formation < 9 Gyr ago for NGC 4472 (Humphrey & Buote 2006; Gallagher et al. 2008), at which time the stellar abundances are established. The internal sources of mass and metals are stellar mass loss – calculated using remnant masses and main sequence turnoff times from the literature – and SNIa explosions. Effects of outflow (including the possibility of a mismatch between the metallicity of the gas in the galaxy and that flowing out of the galaxy), initial conditions, and different time dependencies for the mass return and SNIa rates are considered. For a set of simple one-zone models (“closed-box”, and “tracking” solutions where mass return and SNIa have the same time-dependence – steady state solutions are a subset of the latter), we solve the equations expressing the conservation of overall ISM mass and mass of the i th element for the present-day ISM abundances. For these simple models, solutions generally are of the form

$$f_{\text{ISM}}^i = r f_{\text{stars}}^i + sq y_{\text{SNIa}}^i, \quad (1)$$

where f_{ISM}^i and f_{stars}^i are the i th element ISM and stellar mass fractions, respectively; r is a stellar mass loss dilution ($r < 1$) or enhancement ($r > 1$) factor, and sq is a term that determines the importance of SNIa enrichment relative to that from stellar mass loss. As explained in Sections A1-3, q is the ratio of present-day SNIa to mass return rate, $q = 0.00667 \theta_{\text{SNIa}} / \theta_{\text{MR}} M_{\odot}^{-1}$, where θ_{MR} is the specific mass loss rate in units of $2.4 \cdot 10^{-11} M_{\odot} \text{yr}^{-1} L_{\text{B}\odot}^{-1}$ (we henceforth assume $\theta_{\text{MR}} = 1$), and θ_{SNIa} is the specific SNIa rate in units of 0.16 SNU (Cappellaro et al. 1997). The dimensionless r and s parameters may be element-dependent, but we do not consider that generalization here. The input parameters are (1) the stellar $[\alpha/\text{Fe}]$ ratio that we use to determine the stellar abundance pattern using (IMF-weighted, solar metallicity progenitor) SNII+HN (hypernova) and SNIa yields from Nomoto et al. (1997); Kobayashi et al. (2006), (2) the ratios of the SNIa yields for each element relative to that of Fe, (3) the ratio of ISM Fe abundance to stellar Fe abundance, and (4) the dilution parameter r . The output is the ISM abundance pattern relative to Fe. Specifying the ISM and stellar Fe abundances and SNIa yields (not just the ratios), determines sq and the predicted values of the ISM abundances. The r and sq

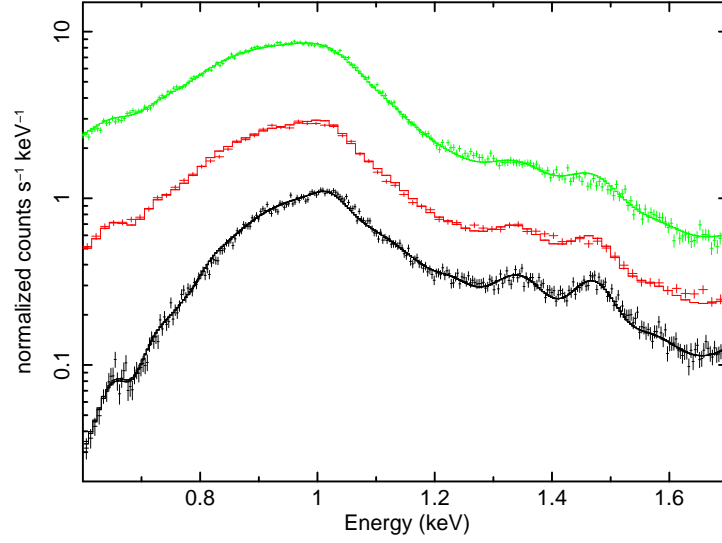
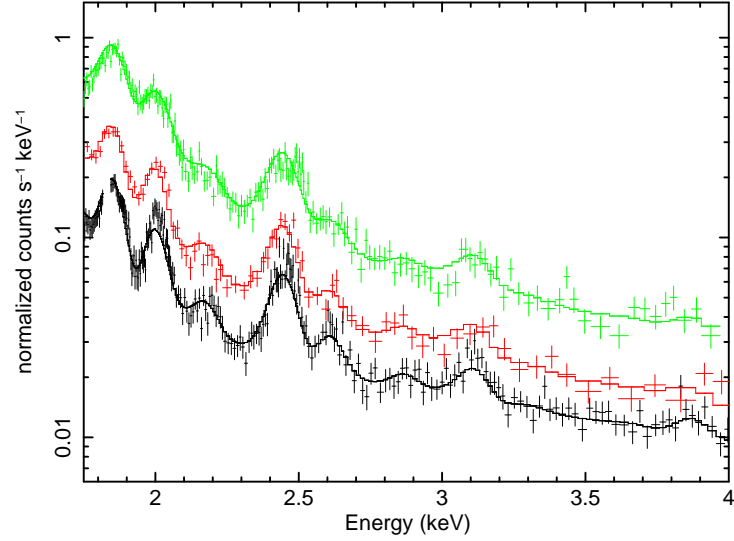


Fig. 8.— **top (a)**: MOS1 (red), pn (green), and XIS0 (black) inner region spectra in the 0.6–1.7 keV bandpass. **bottom (b)**: Same for 1.75–4 keV bandpass.



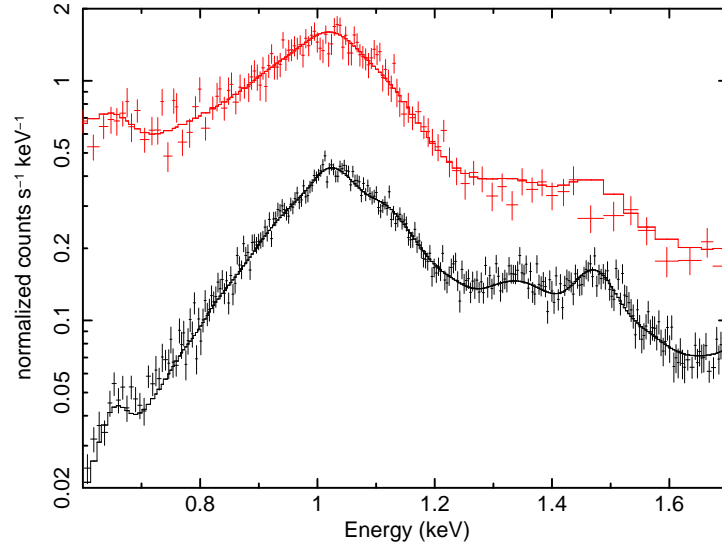
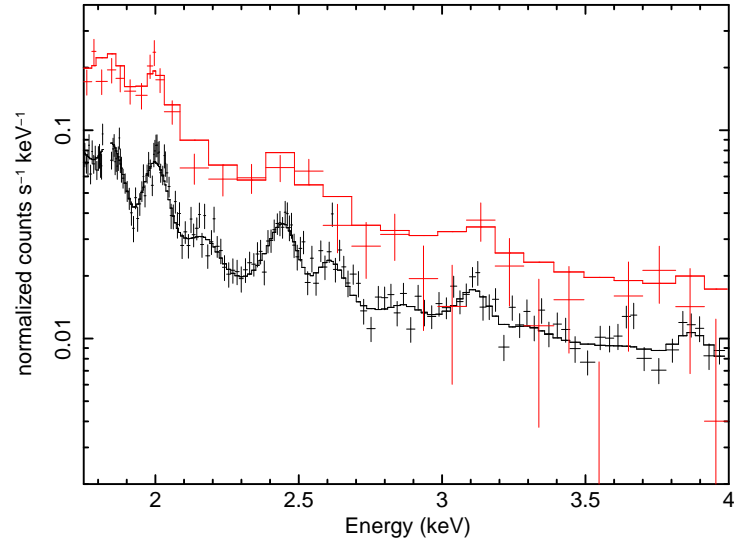


Fig. 9.— **top (a)**: pn (red), and XIS0 (black) outer region spectra in the 0.6–1.7 keV bandpass. **bottom (b)**: Same for 1.75–4 keV bandpass.



parameters can then be interpreted in terms of relative SNIa frequency, outflow parameters, and initial condition in the context of different models (Section A3). We generally consider $[\alpha/Fe]_{\text{stars}} = 0.25, 0.15, 0, -0.2$ (where the sum used to compute α includes only those elements measured in the ISM), an ISM/stellar Fe abundance ratio 1.65 based on a gas-mass weighted average of our inner and outer region *Suzaku* abundances and the stellar Fe abundance from Humphrey & Buote (2006), and $r = 1, 2/3, 1/3$.

A value of $r < 1$ may be explained in several ways (Sections A.1-A.3). In the steady-state models we consider, $r = 1/3$ ($2/3$) corresponds to an outflow bias of 2.0 (0.5) – i.e., that gas is outflowing with $1.5\times$ ($3.0\times$) the mean metallicity inside the galaxy; $r = 1$ corresponds to no such bias. For the closed box models with the extreme initial condition of 0 initial ISM metallicity, $r = 1/3$ ($2/3$) corresponds to having two-thirds (one-third) of the present-day ISM mass at 84% (91%) of the Hubble time. The dilution is attributed to this preexisting low-metallicity gas; $r = 1$ corresponds to (the reasonable) initial conditions where the ISM and stellar abundances are equal. For tracking solutions, where winds are driven by SNIa and the mass return and SNIa rates have identical time-dependencies, we can also consider the extreme case where the ISM metallicity is 0 at the initial time of 0.7 of the Hubble time. Here, $r = 1/3$ ($2/3$) corresponds to having $1.8\times$ ($35\times$) the current ISM mass. The dilution is due to the large initial reservoir of low-metallicity gas that is driven out of the galaxy while being replenished by SNIa-enriched stellar mass return; $r = 1$ again corresponds to (the reasonable) initial conditions where the ISM and stellar abundances are equal.

We consider two sets of SNIa yields from Nomoto et al. (1997) – the standard W7 deflagration model, and the WDD1 delayed detonation model that represents the most radical departure from W7 in terms of nucleosynthetic yields. A comparison of the *Suzaku*-derived ISM abundance pattern inside the optical galaxy (the gas-mass weighted sum of our inner and outer abundances) and the implied stellar abundance pattern is shown in Figure 10. For stellar abundances derived using the W7 yields, the ISM abundances are similar to those in the stars assuming a solar or slightly supersolar $[\alpha/Fe]_{\text{stars}}$ – with the notable exceptions of ISM overabundances of Ar and Ca and an underabundance of O (all relative to Fe). For the WDD1 yields, the ISM again is similar to the $[\alpha/Fe]_{\text{stars}} \sim 0$ pattern, but now Ni is overabundant while O and S are underabundant in the ISM. Since direct SNIa enrichment is expected to distort the ISM pattern relative to that in the stars, these comparisons should be considered referential; however, some of these anomalies persist.

To review how we compare these models with the observed abundances, sufficient SNIa enrichment (value of sq) is added to the diluted (since we consider $r \leq 1$) stellar Fe abundance to match the observed ISM Fe abundance. The SNIa rate corresponding to “sufficient enrichment” is model-dependent – but only weakly so for quiescent systems, where $s \approx r$, i.e.

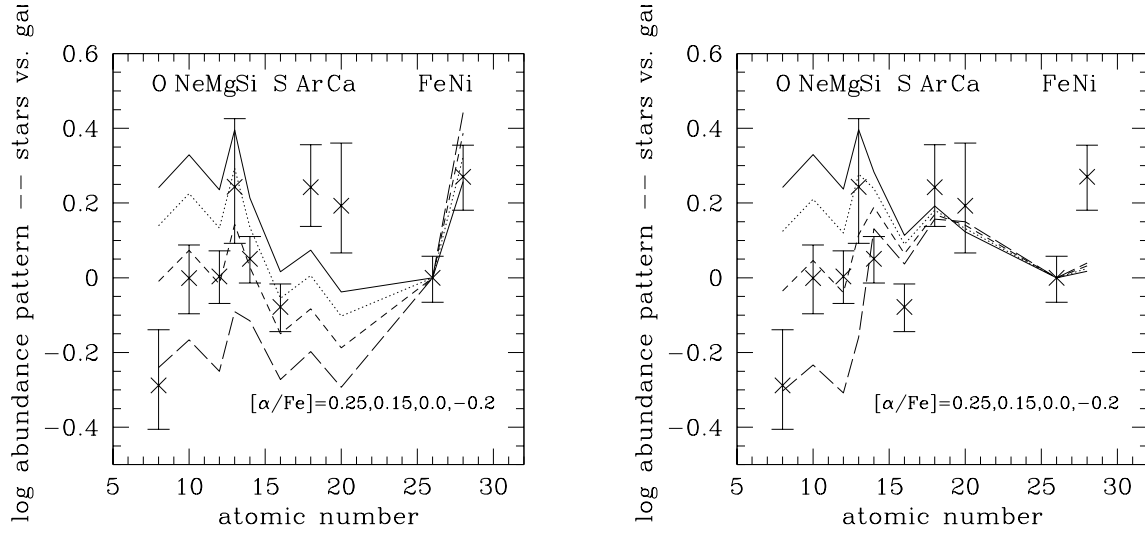


Fig. 10.— Comparison of abundances (including Al – located between Mg and S), relative to Fe, in the ISM (crosses with errorbars) and that expected in the stars for the cases where W7 SNIa (**a, left**) and WDD1 (**b, right**) SNIa yields (Nomoto et al. 1997) are used in conjunction with SNII+HN yields from Kobayashi et al. (2006) to set the stellar abundance pattern for a given $[\alpha/\text{Fe}]_{\text{stars}}$. Shown are $[\alpha/\text{Fe}]_{\text{stars}}=0.25$ (solid line), 0.15 (dotted), 0.0 (short-dashed) and -0.2 (long-dashed).

$q \approx (sq)/r$ or $\theta_{\text{SNIa}} \approx 150(sq)/r$. The magnitudes of the stellar mass loss and SNIa terms are now set and may be used, in conjunction with the stellar abundance pattern and SNIa yields, to determine the entire ISM pattern. Figure 11 compares model predictions of the ISM abundances with the observations for the case where W7 yields are adopted; θ_{SNIa} corresponding to $s = r$ is indicated³. The abundances of Ne, Mg, Al, Si, S and Ni are well-explained as a combination of undiluted ($r = 1$) stellar mass loss from stars with $[\alpha/Fe]_{\text{stars}}=0.25$ and SNIa enrichment at a rate approximately one-sixth the standard early-type galaxy value, $\theta_{\text{SNIa}} = 0.17$ (Figure 11a). However, Ar and Ca are underpredicted by factors of order 2 and O overpredicted by a similar factor. On the other hand the model with sufficient dilution to imply $\theta_{\text{SNIa}} = 1$ for a steady-state model ($r = 1/3$), the expected low ratios with respect to Fe of Ne, Mg, Al, Si, S, Ar, Ca are greatly at odds with the observations; and, the Ni/Fe ratio is overpredicted (Figure 11b). In the limit where the stellar abundances are purely determined by SNII ($[\alpha/Fe]_{\text{stars}} \sim 0.43$), the ISM O-to-Fe ratio is reproduced but all other ratios with respect to Fe are not (Figure 11b).

The WDD1 models, where SNIa produce more Si, S, Ar, and Ca and less Fe and Ni, $r = 1$ models with supersolar $[\alpha/Fe]_{\text{stars}}$ now adequately explain the ratios, with respect to Fe, of Ne, Mg, Al, Ar, and Ca but overpredict Si (slightly) and S as well as O (Figure 12a). Ni is underpredicted by ~ 2 , as it is for the $r = 1/3$ model. In the latter (Figure 12b), Si and O are matched by models with $[\alpha/Fe]_{\text{stars}}$ corresponding to a pure SNII origin, but Ne and Mg are now underpredicted.

5. Discussion

In the most natural models – whether they resemble the closed box, steady state, or slightly more complex outflow models considered here – abundances (expressed as mass fractions) in the hot ISM of elliptical galaxies should be well-approximated by

$$f_{\text{ISM}}^i(1) = f_{\text{stars}}^i + 0.00667\theta_{\text{SNIa}}y_{\text{SNIa}}^i. \quad (2)$$

Figures 11 and 12 clearly show that the modest overabundance of interstellar Fe with respect to that in the stars, and the nearly solar abundance ratios of Ne, Mg, Si, and S with respect to Fe in NGC 4472, are consistent with this expectation provided that $\theta_{\text{SNIa}} \sim 0.2$ and

³We note here that our results are not sensitive to our adoption of the Grevesse & Sauval (1998) solar abundance standard, since all quantities are scaled on this basis. Adoption of a different standard would shift observed and model abundances in lockstep, although the value of $[\alpha/Fe]_{\text{stars}}$ corresponding to a given model would shift somewhat

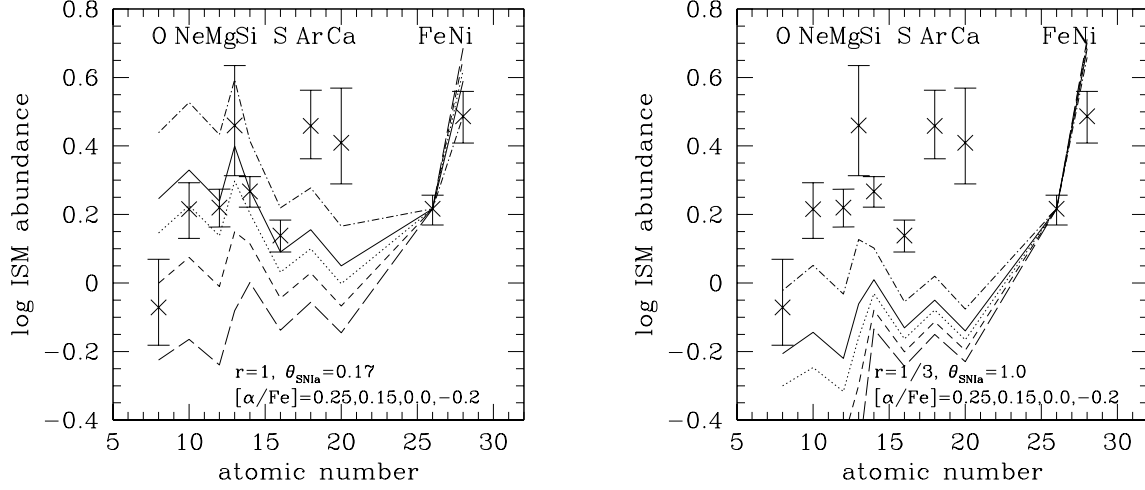


Fig. 11.— Comparison of abundances (including Al – located between Mg and S), relative to Fe, in the ISM (crosses with errorbars) and those predicted in models where W7 SNIa yields are adopted for $r = 1$ (**left a:**) and $r = 1/3$ (**right b:**). Shown are $[\alpha/Fe]_{\text{stars}}=0.25$ (solid line), 0.15 (dotted), 0.0 (short-dashed) and -0.2 (long-dashed). Additionally, the $[\alpha/Fe]_{\text{stars}} = 0.45$ (pure SNIa stellar abundances) model is shown (dot-dashed line).

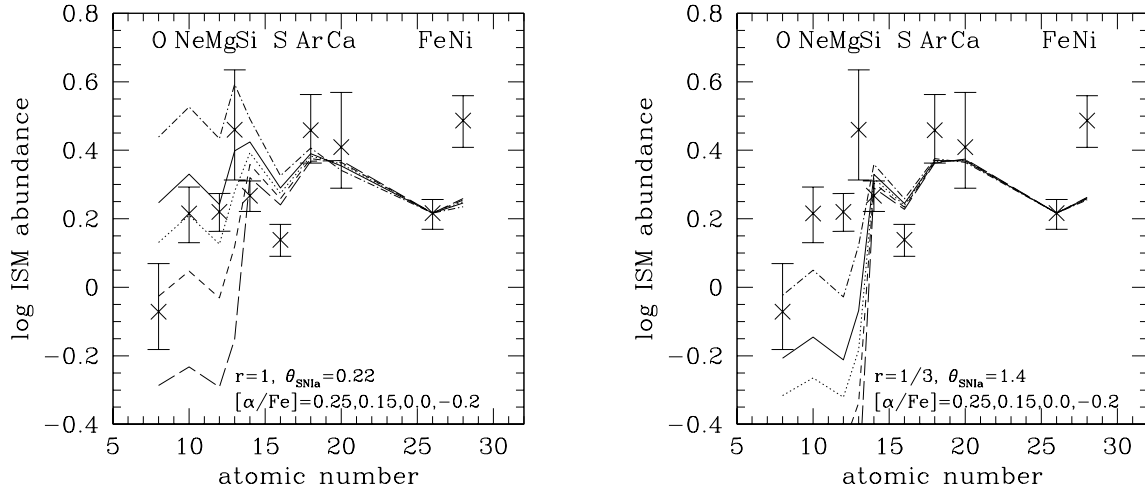


Fig. 12.— Same as Figure 11 for WDD1 SNIa yields.

$[\alpha/Fe]_{\text{stars}} \sim 0.2$. We thus confirm the inference, based on optical data, that the stars in elliptical galaxies have supersolar $[\alpha/Fe]$ ratios – and infer that this extends globally. The relative Fe abundances may be accommodated in models with $\theta_{\text{SNIa}} \sim 1$ only by introducing mechanisms such as preferential outflow of metal rich gas, or assuming that the ISM has built up its Fe abundance relatively recently from substellar values either as the ISM mass itself has increased (for a closed box), or in concert with strong outflows. However, the ISM abundance pattern is poorly reproduced in such models for virtually all elements measured in the NGC 4472 ISM irrespective of the assumed $[\alpha/Fe]_{\text{stars}}$.

While we consider only a single galaxy, large ISM-to-stellar Fe abundance ratios have not been measured in any elliptical galaxy (see references in Section 1.2). There is thus a conflict between the canonical elliptical galaxy SNIa rate (Cappellaro et al. 1997) and the Fe abundance in the hot ISM of ellipticals. One avenue of reconciliation is to presume that the *effective* rate of SNIa enrichment is much less than the actual rate because SNIa are not efficiently well-mixed into the ISM. This implies that there is large amount of Fe left unaccounted.

It is plausible that there is substantial galaxy-to-galaxy variation in the current SNIa rates of elliptical galaxies. Galaxies that are radio loud or have blue colors have been shown to have enhanced SNIa rates (Mannucci et al. 2005; Della Valle et al. 2005). Currently quiescent galaxies may be sampling the tail-end of a SNIa delay-time distribution with a peak at one or more timescales much less than the Hubble time, and the rates may be sensitive to the strength and lookback time of minor star formation episodes. If this is the case, galactic winds might be induced in those galaxies with the highest rates, rendering them gas poor and X-ray dim, and creating an observational bias tilted towards ellipticals with low SNIa rates.

There are robust anomalies in the abundance pattern that cannot be explained using any of the standard yields (Figures 11 and 12). The ISM abundances of O, Ne, and Mg are overwhelmingly determined by SNII ejecta incorporated into, and then ejected, by evolved stars. Therefore, the NGC 4472 O underabundance - universally replicated in other elliptical galaxy hot (Humphrey & Buote 2006; Ji et al. 2009) and warm (Athey & Bregman 2009) ISM – can only be explained by decreasing the O abundance in mass losing stars that, in turn, implies a reduction in (IMF-weighted average) SNII yield by about a factor of 2. This is not physically unreasonable considering the sensitivity of SNII production of O to the treatment of convection in the progenitor stars (Gibson, Loewenstein, & Mushotzky 1997). Alternatively, one could reduce the predicted O yields by a truncation of the IMF, since O yields increase steeply with progenitor mass; however, the mass dependence of Ne and Mg yields are nearly as steep. These results for O are especially significant since the $[O/H]$

abundance in HII regions is often used as a proxy for overall metallicity in studies of galaxies with star formation (Garnett 2002; Kobulnicky & Kewley 2004). Interpretation of such data assuming solar ratios among α -elements and standard O yields should be considered with caution, as should calibration of SN-induced feedback in semi-analytic models that are based on observed O abundances.

Another evident abundance pattern anomaly manifests as simultaneously high ISM abundances of Ar, Ca, and Ni. While application of W7 models can explain the high Ni/Fe ratio, it underpredicts Ar and Ca (Figure 11); the converse is true for models utilizing the WDD1 SNIa yields. For the $r = 1$, $[\alpha/Fe]_{\text{stars}}=0.15$ and 0.25 models with W7 SNIa yields, stellar mass loss accounts for $> 80\%$ of O, Ne, Mg, Al, Si, S, Ar, and Ca, $\sim 60\%$ of Fe, and $\sim 50\%$ of Ni in the hot ISM with the remaining metals originating from direct enrichment via SNIa. To “fix” the Ca and Ar discrepancy by increasing the stellar mass loss abundances through a boost in the SNII Ar and Ca yields is not very appealing, since Ca is not overabundant (with respect to Mg) in red-sequence galaxies (Graves et al. 2007; Smith et al. 2009) – in fact, Ca traces Fe more closely than it does Mg (Graves et al. 2007), which argues for an important SNIa contribution to Ca. In Table 2 and Figure 13, we show the output for an $r = 1$ ($\theta_{\text{SNIa}} \sim 0.25$), $[\alpha/Fe]_{\text{stars}}=0.15$ model with the following *ad hoc* yield adjustments: a decrease in the average SNII O yield by a factor 2, and SNIa yields for Ca, Ar, Fe, and Ni of 0.05, 0.05, 0.5, and 0.07 M_{\odot} , respectively. One can see that, in such models, direct SNIa enrichment and enrichment via stellar mass return from material originating in SNIa and in SNII all make significant contributions to these elements, while the abundances of the lower-Z elements predominately originate in SNII products incorporated into stars. This is not meant as a definitive proposal, but to illustrate the sort of adjustments required. Should such abundance pattern anomalies prove prevalent, genuine constraints on supernova yields may be derived (Loewenstein, et al. in preparation).

Table 2. *Ad hoc* Model Yields and Origins

	y_{SNIa}	y_{SNII}	stars	stars:SNIa	stars:SNII	direct:SNIa
O	0.14	0.7	0.97	0.021	0.94	0.034
Ne	0.0045	0.38	1.0	0.0013	1.0	0.0021
Mg	0.0086	0.12	0.99	0.0080	0.98	0.013
Al	0.00099	0.014	0.99	0.0074	0.98	0.012
Si	0.15	0.11	0.82	0.11	0.71	0.18
S	0.086	0.047	0.79	0.13	0.65	0.21
Ar	0.05	0.0077	0.60	0.25	0.35	0.40
Ca	0.05	0.0054	0.55	0.28	0.27	0.45
Fe	0.5	0.083	0.61	0.24	0.36	0.39
Ni	0.07	0.041	0.49	0.32	0.17	0.51

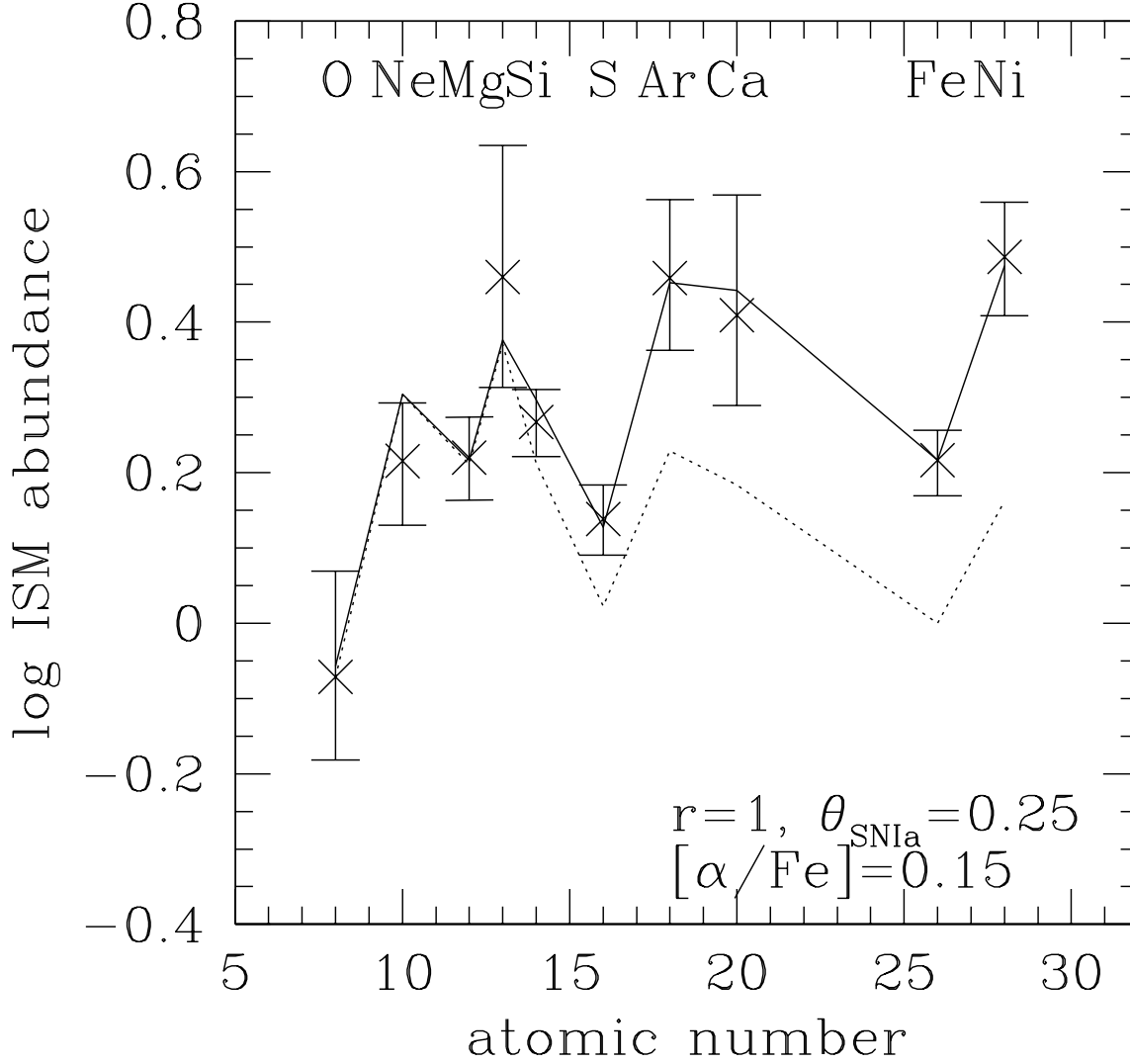


Fig. 13.— Comparison of abundances (including Al – located between Mg and S), relative to Fe, in the ISM (crosses with errorbars) and those predicted in a model where *ad hoc* yields for some elements (see text, Table 2) are adopted for $r = 1$, $[\alpha/\text{Fe}]_{\text{stars}}=0.15$ ($\theta_{\text{SNIa}} \sim 0.25$). The latter is indicated by the solid line; stellar abundances are shown by the dotted line.

6. Summary and Conclusions

We have derived the hot ISM abundance pattern in inner ($0 - 2.3R_e$) and outer ($2.3 - 4.6R_e$) regions of NGC 4472 from analysis of *Suzaku* spectra and used them to study the chemical evolution in this elliptical galaxy. The low *Suzaku* background and relatively sharp spectral resolution of the *Suzaku* XIS detectors enabled us to extend the range of accurately measured abundances beyond what is feasible with *Chandra* or *XMM-Newton* to S, Ar, Ca, and possibly Al – while we find general agreement with overlapping *XMM-Newton* results. The abundances of Ne, Mg, Si, S, Fe, and Ni may be explained by enrichment via a combination of α -element enhanced stellar mass loss and direct injection of SNIa with W7 yields exploding at a current rate of 0.027 SNU; however, additional SNIa production of Ca and Ar is required. Ca and Ar are reproduced in models (with a SNIa rate of 0.035 SNU) where WDD1 yields are adopted, but at the price of disrupting the previous concordance for S and Ni.

Models with the standard SNIa rate of 0.16 SNU badly overpredict Fe, unless the enrichment from stellar mass loss is diluted. We introduced models where this is a consequence of outflow biased in favor of high metallicity, or an inertial effect resulting from the preexistence of a metal poor ISM. However, such models predict an underabundance of elements primarily synthesized in SNII (Ne and Mg for W7 and WDD1 SNIa yields, and Si, S, Ar, and Ca as well for W7) and offer a poorer match to the observed abundance pattern.

We confirm previous measurements of a low O abundance; the low O/Mg and O/Ne ratios imply that the SNII yields in standard models overproduce O by ~ 2 .

Analysis of additional *Suzaku* and *XMM-Newton* spectra of elliptical galaxies will be used to investigate the universality of these results, and probe for diversity in the star formation and SNIa histories of giant elliptical galaxies. Application of more rigorous chemical evolution models will sharpen these conclusions, and should yield new information on the formation and evolution of these systems and indirect constraints on the physics of Type Ia supernovae.

A. Simple Models for Elliptical Galaxy Hot ISM Abundances

A.1. Formalism

In this paper we apply a simplified chemical evolution formalism to the NGC 4472 observations. A more comprehensive treatment and application of the coupled chemical evolution of the gas and stars in elliptical galaxies is in progress.

For a single-phase interstellar medium in a passively evolving galaxy – good approximations for giant elliptical galaxies in general, and NGC 4472 in particular – the equations for the conservation of overall ISM mass, M_{ISM} , and mass of the i th element, $f_{\text{ISM}}^i M_{\text{ISM}}$ where f_{ISM}^i is the mass fraction, are as follows:

$$\frac{dM_{\text{ISM}}}{dt} = \dot{M}_{\text{MR}} - \dot{M}_{\text{out}}, \quad (\text{A1})$$

and

$$\frac{d(f_{\text{ISM}}^i M_{\text{ISM}})}{dt} = G_{\text{SNIa}}^i + G_{\text{MR}}^i - (1 + b_{\text{out}}^i) \dot{M}_{\text{out}} f_{\text{ISM}}^i. \quad (\text{A2})$$

The only significant internal source of gas is stellar mass return (injected at the rate \dot{M}_{MR}), while metals are provided by Type Ia supernovae (rate G_{SNIa}^i) as well as stellar mass loss (rate G_{MR}^i). \dot{M}_{out} accounts for gas flowing in or out of the optical galaxy (and is positive for outflow). The “bias” factor b_{out}^i allows for an offset between the in- or outflowing gas metallicity and the mass-weighted-average inside the galaxy; henceforth we assume this is identical for all elements and suppress the index. For $b_{\text{out}} > (<)0$ winds serve to reduce (increase) the overall galactic ISM metallicity, while for $b_{\text{out}} = 0$ winds remove metals but do not change the overall metallicity. For inflow, $b_{\text{out}} > (<)0$ increases (reduces) the galactic ISM metallicity,

These equations may be integrated from the end of the galaxy formation era t_{in} (at which time it is assumed that the galaxy is fully assembled and star formation has ceased) to the present day t_{now} (13.7 Gyr). It is sensible to “start the clock” at t_{in} since we know that the ISM mass inside the optical galaxy today is much less than the stellar mass return rate integrated over the galaxy lifetime. The star formation era *must* have been accompanied by prodigious outflows in a multiphase ISM, and cannot be modeled using the formalism developed here. Following Ciotti et al. (1991), and utilizing main sequence turnoff masses and remnant masses from Schaller et al. (1992) and Salaris et al. (2009), respectively, we derive $\dot{M}_{\text{MR}} \approx AL_B(t/t_{\text{now}})^{-\alpha}$, where $\alpha \approx 1.3$, $A \approx 2.4 \cdot 10^{-11} \theta_{\text{MR}} M_{\odot} \text{yr}^{-1} L_B \odot^{-1}$ and $\theta_{\text{MR}} = 1$ for a simple stellar population with present-day blue luminosity L_B . In this simple case $G_{\text{MR}}^i = \dot{M}_{\text{MR}} f_{\text{stars}}^i$, where f_{stars}^i is the (constant after t_{in}) mass fraction of the i th-element in evolved (mass-losing) stars. The SNIa enrichment term $G_{\text{SNIa}}^i = \dot{N}_{\text{SNIa}} y_{\text{SNIa}}^i$, where y_{SNIa}^i is the i th element SNIa mass yield. The SNIa rate may be characterized as $\dot{N}_{\text{SNIa}} \approx BL_B(t/t_{\text{now}})^{-\beta}$ with $B = 1.6 \cdot 10^{-13} \theta_{\text{SNIa}} \text{yr}^{-1} L_B \odot^{-1}$; $\theta_{\text{SNIa}} = 1$ corresponds to the rate of Cappellaro et al. (1997). Ciotti et al. (1991) adopt $\beta = 1.1$ and $\theta_{\text{SNIa}} = 1$, while in the models of Ruiter, Belczynski, & Fryer (2009) substantially lower rates, and a somewhat steeper decline, are

derived from binary population synthesis. In some models we assume that there is an outflow that is driven by SNIa and given by $\dot{M}_{\text{out}} = K_{\text{out}} \dot{N}_{\text{SNIa}} M_{\text{ISM}}$, where K_{out} is a dimensionless constant.

A.2. Special Cases with Exact Solutions

It proves convenient to introduce the following dimensionless variables: $\tau \equiv t/t_{\text{now}}$, $\mu \equiv M_{\text{ISM}}/M_{\text{ISM}}(t_{\text{now}})$, $\phi^i = f_{\text{ISM}}^i/f_{\text{stars}}^i$, $\psi = \dot{M}t_{\text{now}}/M_{\text{ISM}}(t_{\text{now}})$, $\gamma^i = G^i t_{\text{now}}/(M_{\text{ISM}}(t_{\text{now}})f_{\text{stars}}^i)$. Equations (A1) and (A2) become

$$\frac{d\mu_{\text{ISM}}}{d\tau} = \psi_{\text{MR}} - \psi_{\text{out}}, \quad (\text{A3})$$

and

$$\frac{d(\phi_{\text{ISM}}^i \mu_{\text{ISM}})}{dt} = \gamma_{\text{SNIa}}^i + \gamma_{\text{MR}}^i - (1 + b_{\text{out}})\psi_{\text{out}}\phi_{\text{ISM}}^i, \quad (\text{A4})$$

with $\mu(1) = 1$ and the following boundary conditions at $\tau_{\text{in}} = t_{\text{in}}/t_{\text{now}}$: $\mu_{\text{in}} \equiv M_{\text{ISM}}(t_{\text{in}})/M_{\text{ISM}}(t_{\text{now}})$ and $\phi_{\text{ISM,in}}^i \equiv f_{\text{ISM}}^i(t_{\text{in}})/f_{\text{stars}}^i$. The source terms are $\psi_{\text{MR}} = \psi_o \tau^{-\alpha}$, $\gamma_{\text{MR}}^i = \psi_{\text{MR}}$, $\gamma_{\text{SNIa}}^i = \epsilon^i \eta_o \tau^{-\beta}$, with $\psi_o = A(M_{\text{ISM}}(t_{\text{now}})/L_B)t_{\text{now}}$, $\eta_o = B(M_{\text{ISM}}(t_{\text{now}})/L_B)t_{\text{now}}$, and $\epsilon^i = y_{\text{SNIa}}^i/f_{\text{stars}}^i$; for SNIa-driven galactic winds $\psi_{\text{out}} = \kappa \eta_o \tau^{-\beta} \mu$, where $\kappa = K_{\text{out}} M_{\text{ISM}}(t_{\text{now}})$. $Q^i = \eta_o \epsilon^i / \psi_o = (B/A)\epsilon^i$ and $W = \kappa \eta_o / \psi_o = (B/A)\kappa$ are convenient dimensionless quantities that factor into determining the importance of SNIa metal enrichment and outflows, respectively.

There are two classes of simple analytic solutions to equations (A3) and (A4) – closed box models where $\dot{M}_{\text{out}} = 0$, and “tracking” solutions where $\alpha = \beta$. Subsets of the latter include steady-state solutions (only exactly possible if $\alpha = \beta$), and solutions where the ISM mass is in a steady state, but its metallicity is not (i.e., abundances are evolving much more quickly than the total mass).

For closed box models, the dimensionless abundances at the present day are given by

$$\phi_{\text{ISM}}^i(1) = 1 - \mu_{\text{in}}(1 - \phi_{\text{ISM,in}}^i) + \frac{Q^i \psi_o}{(1 - \beta)}(1 - \tau_{\text{in}}^{1-\beta}), \quad (\text{A5})$$

where μ_{in} or τ_{in} may be eliminated using

$$\mu_{\text{in}} = 1 - \frac{\psi_o}{(1 - \alpha)}(1 - \tau_{\text{in}}^{1-\alpha}). \quad (\text{A6})$$

This takes a particularly simple form for the reasonable initial conditions $\phi_{\text{ISM},\text{in}}^i = 1$ (identical ISM and stellar metallicities) and/or $\mu_{\text{in}} = 0$ (galaxy evacuated of gas at the close of the star formation era).

A steady state is possible if $\alpha = \beta$. The dimensionless ISM mass fraction at all times in this case is given by

$$\phi_{\text{ISM}}^i = \frac{(1 + Q^i)}{(1 + b_{\text{out}})}. \quad (\text{A7})$$

We also consider the general $\alpha = \beta$ case with SNIa-driven outflow and $b_{\text{out}} = 0$. In this case, the solution is

$$\phi_{\text{ISM}}^i(1) = \frac{(1 + Q^i)(1 - \mu_{\text{in}}) + \mu_{\text{in}}\phi_{\text{ISM},\text{in}}^i(1 - W)}{1 - W\mu_{\text{in}}}, \quad (\text{A8})$$

where W and μ_{in} are related to τ_{in} via

$$\mu_{\text{in}} = W^{-1} \{1 - (1 - W)\exp[W\psi_o(1 - \tau_{\text{in}}^{1-\alpha})/(1 - \alpha)]\} \quad (\text{A9})$$

A.3. General Features and Application

All of the simple models above have solutions of the form

$$\phi_{\text{ISM}}^i(1) = r^i + sq\epsilon^i, \text{ i.e.} \quad (\text{A10})$$

$$f_{\text{ISM}}^i(1) = r^i f_{\text{stars}}^i + sqy_{\text{SNIa}}^i, \quad (\text{A11})$$

where $q = B/A$ is proportional to the present-day ratio of SNIa to mass return rate. For the simplest steady state models ($r^i = s = 1$) mass return enriches the ISM to the stellar metallicity (first term), and SNIa further enhances the abundances according to the ratio of supernova to mass-loss rates and the SNIa yield. In the other models considered above r represents dilution or amplification of stellar mass return due to initial conditions for closed box models, biased outflow in the steady-state $b_{\text{out}} \neq 0$ case, and the interplay between initial conditions and outflow for the tracking solutions. The factor sq represents the SNIa enrichment and depends on the ratio of supernova to mass-loss rates with these same causes of dilution/amplification for the steady-state $b_{\text{out}} \neq 0$ and tracking solutions, and modification due to the mismatch in the SNIa and stellar mass loss time dependencies for the close box case.

In particular (see Table 3) $r^i = (1 + b_{\text{out}})^{-1}$ for steady state, $r^i = 1 - \mu_{\text{in}}(1 - \phi_{\text{ISM},\text{in}}^i)$ for closed box, and $r^i = [(1 - \mu_{\text{in}}) + \mu_{\text{in}}\phi_{\text{ISM},\text{in}}^i(1 - W)]/(1 - W\mu_{\text{in}})$ for tracking solutions. The

SN Ia parameter $s = (1 + b_{\text{out}})^{-1}$ for steady state, $s = \psi_o(1 - \tau_{\text{in}}^{1-\beta})/(1 - \beta)$ for closed box, and $s = (1 - \mu_{\text{in}})/(1 - W\mu_{\text{in}})$ for tracking solutions.

One can relate the ISM abundances of the i th and j th elements, eliminating the factor s , via

$$f_{\text{ISM}}^i(1) = r f_{\text{stars}}^i + (f_{\text{ISM}}^j(1) - r f_{\text{stars}}^j) \frac{y_{\text{SN Ia}}^i}{y_{\text{SN Ia}}^j} \quad (\text{A12})$$

or

$$\frac{f_{\text{ISM}}^i(1)}{f_{\text{ISM}}^j(1)} = \frac{f_{\text{stars}}^i}{f_{\text{stars}}^j} \frac{f_{\text{stars}}^j}{f_{\text{ISM}}^j(1)} r + \left(1 - r \frac{f_{\text{stars}}^j}{f_{\text{ISM}}^j(1)}\right) \frac{y_{\text{SN Ia}}^i}{y_{\text{SN Ia}}^j}, \quad (\text{A13})$$

where we have made the simplifying assumption that $r^i = r$ is the same for all elements (already implied for steady state solutions by adopting constant b_{out} , and otherwise equivalent to constant $\phi_{\text{ISM, in}}^i$ – i.e., an element-independent initial ratio of ISM-to-stellar abundances).

In the approach we adopt here, we calculate the ISM abundance pattern for a given stellar abundance pattern (corresponding to a particular $[\alpha/\text{Fe}]$ ratio; see below) and ISM-to-stellar Fe abundance, for a range of values of r . One then compares the pattern with the NGC 4472 observations to see if consistent scenarios emerge and to identify any anomalies. The parameter r may then be interpreted *post facto* under the different classes of models, as can s for values of the stellar and ISM Fe abundances (and not just the ratios). We consider the SNIa and SNII yields from Nomoto et al. (1997); Kobayashi et al. (2006), and use these to set the stellar abundance pattern for a given value of $[\alpha/\text{Fe}]_{\text{stars}}$, where $[\alpha/\text{Fe}]$ is defined as follows. We calculate the ratio, with respect to the Fe mass fraction, of the sum of the mass fractions of all elements under consideration lighter than Fe, divide by the same ratio calculated using the Grevesse & Sauval (1998) solar standard, and take the logarithm. For a given set of yields, $[\alpha/\text{Fe}]$ corresponds to a particular number ratio of SNIa to SNII that contributed to establishing the stellar abundances. The same set of yields are used for SNIa that directly enrich the ISM, and those that enrich the stars.

As it turns out, numerical experiments demonstrate that $s \approx r$ for most reasonable models. This is exactly true for the steady state models. For closed box models with

Table 3. Definitions for r and s in Different Models

Model	r^i	s
Steady state	$(1 + b_{\text{out}})^{-1}$	$(1 + b_{\text{out}})^{-1}$
Closed Box	$1 - \mu_{\text{in}}(1 - \phi_{\text{ISM, in}}^i)$	$\psi_o(1 - \tau_{\text{in}}^{1-\beta})/(1 - \beta)$
Tracking	$[(1 - \mu_{\text{in}}) + \mu_{\text{in}}\phi_{\text{ISM, in}}^i(1 - W)]/(1 - W\mu_{\text{in}})$	$(1 - \mu_{\text{in}})/(1 - W\mu_{\text{in}})$

$\phi_{\text{ISM},\text{in}}^i = 0$, it deviates by $< 20\%$ for $\theta_{\text{MR}} = 1$, $M_{\text{ISM}}(t_{\text{now}})/L_B \sim 0.1$, and $0 < \beta < 2$. The dependence on $\phi_{\text{ISM},\text{in}}^i$ is flat until one gets to the regime where the solution corresponds to the ISM Fe abundance being substellar until very recently and then suddenly being enriched to the observed superstellar value by a concentrated period of SNIa enrichment. Similarly, for tracking solutions s differs significantly from r only in cases where, at a recent epoch the galaxy was filled with a large mass of low-abundance gas. In this scenario, the galaxy must be experiencing a powerful outflow that has ejected most of the low metallicity gas and replenished it with SNIa-enhanced stellar mass return. For example, using our standard parameters, to obtain $s = 0.5$ for $r = 1$, one requires the galaxy have 6.4 times its present ISM mass at $\tau_{\text{in}} = 0.7$, and with < 0.08 solar Fe abundance. *This implies that, for relatively quiescent elliptical galaxies, for a given value of the dilution factor r the offset between the stellar and ISM Fe abundances (and the SNIa Fe yield) can be robustly used to estimate the SNIa to mass return rate. If the SNIa and mass loss rates have different time-dependencies the ratio will correspond to a ratio of time-averaged rates, but for standard parameters this does not drastically differ from the ratio at the present day.*

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