The Astrophysical Journal, 560:L79–L82, 2001 October 10

DETECTION OF THE 67.9 AND 78.4 keV LINES ASSOCIATED WITH THE RADIOACTIVE DECAY OF ^{44}Ti IN CASSIOPEIA A

Jacco Vink,[1,2] J. Martin Laming,[3] Jelle S. Kaastra,[4] Johan A. M. Bleeker,[4]
Hans Bloemen,[4] and Uwe Oberlack[1]
Received 2001 July 24; accepted 2001 August 31; published 2001 September 17

ABSTRACT

We report the detection of the ^{44}Sc nuclear decay lines at 67.9 and 78.4 keV associated with the nuclear decay of ^{44}Ti in Cassiopeia A. The line emission was observed by the Phoswich Detection System instrument on board *BeppoSAX*, which recently observed the supernova remnant for over 500 ks. The detection of the line emission with a flux of $(2.1 \pm 0.7) \times 10^{-5}$ photons cm^{-2} s^{-1} in each line (90% confidence) is at the 5 σ significance level, if we can assume that the 12–300 keV continuum is adequately represented by a single power law. However, as the nature of the continuum is not clear, we investigate various other possibilities. A more conservative estimate of the line flux is made by assuming that a power-law continuum is at least a good approximation to the continuum emission for a narrower 30–100 keV energy range. With this limitation, the measured line flux is $(1.9 \pm 0.9) \times 10^{-5}$ photons cm^{-2} s^{-1}, with the detection still at the 3.4 σ significance level. We suggest that together with the *Compton Gamma Ray Observatory*/COMPTEL measurement of the ^{44}Ca line at 1157 keV of $(3.3 \pm 0.6) \times 10^{-5}$ photons cm^{-2} s^{-1}, a flux for all three lines of $(2.5 \pm 1.0) \times 10^{-5}$ photons cm^{-2} s^{-1} for Cas A can be adopted. This implies an initial ^{44}Ti mass of $(0.8–2.5) \times 10^{-4}\ M_{\odot}$.

Subject headings: gamma rays: observations — ISM: individual (Cassiopeia A) — nuclear reactions, nucleosynthesis, abundances — supernova remnants — X-rays: ISM

1. INTRODUCTION

The detection of gamma-ray line emission at 1157 keV from the supernova remnant Cassiopeia A by the *Compton Gamma Ray Observatory* (*CGRO*)/COMPTEL (Iyudin et al. 1994) led to renewed interest in the nucleosynthesis and properties of ^{44}Ti, the radioactive element with which this ^{44}Ca nuclear deexcitation emission is associated.

However, the decay chain $^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc} \rightarrow {}^{44}\mathrm{Ca}$ produces two other nuclear deexcitation lines of ^{44}Sc at 67.9 and 78.4 keV with a flux equal to that of the 1157 keV emission (see Diehl & Timmes 1998 for a review). As observations with the hard X-ray instruments *CGRO*/OSSE, *Rossi X-Ray Timing Explorer* (*RXTE*)/High-Energy X-Ray Timing Experiment (HEXTE) and *BeppoSAX*/Phoswich Detection System (PDS) failed to detect those lines (The et al. 1996; Rothschild et al. 1997; Vink et al. 2000), some doubt was cast on the observed 1157 keV line flux, if not on the detection itself. With subsequent observations by COMPTEL, the flux estimates changed from $(7.0 \pm 1.7) \times 10^{-5}$ to $(3.3 \pm 0.6) \times 10^{-5}$ photons cm^{-2} s^{-1} (Iyudin 1997), whereas an 83 ks *BeppoSAX*/PDS spectrum narrowed the ^{44}Sc fluxes to a 99.7% upper limit of 4.1×10^{-5} photons cm^{-2} s^{-1} (Vink et al. 2000).

In this Letter, we report on a new, deep exposure of Cas A with the *BeppoSAX* X-ray observatory. The *BeppoSAX*/PDS spectrum from this observation, together with archival data, finally gives a reliable estimate of the 67.9 and 78.4 keV line fluxes.

[1] Columbia Astrophysics Laboratory, Columbia University, MC 5247, 550 West 120th Street, New York, NY 10027; jvink@astro.columbia.edu, oberlack@astro.columbia.edu.

[2] *Chandra* fellow.

[3] Naval Research Laboratory, 4555 Overlook Avenue, SW, Code 7674L, Washington, DC 20375; jlaming@ssd5.nrl.navy.mil.

[4] Space Research Organization of the Netherlands (SRON), Sorbonnelaan 2, NL-3584 CA, Utrecht, Netherlands; j.s.kaastra@sron.nl, j.bleeker@sron.nl, j.b.g.m.bloemen@sron.nl.

2. OBSERVATIONS AND DATA

In May and June of this year, *BeppoSAX* observed Cas A for more than 500 ks. The primary goal of this observation was to detect the 67.9 and 78.4 keV nuclear decay lines with the hard X-ray detector PDS (Frontera et al. 1997). The PDS consists of four NaI (Tl)/CsI (Na) scintillation detectors behind two rocking collimators with a 1°.3 field of view. During the observation, the collimators switch back and forth between the on-source position and two opposite off-source positions, such that always one collimator observes the source and the other the background. Due to the alternating position of the collimators, the effective exposure of the source with the PDS is about half the total observation time. In this case, the effective PDS exposure is 256 ks. We used additional archival PDS spectra of on-source Cas A observations, resulting in a total effective PDS exposure[5] of 311 ks.

As explained in the *BeppoSAX* analysis cookbook (Fiore, Guainazzi, & Grandi 1999), the standard software pipeline incorporates two methods for rejection of background events due to energetic particles. The more advanced method, which is preferred for a background-dominated source like Cas A, uses a variable, energy-dependent, rise-time rejection threshold. This results in a better particle rejection, but at the cost of a 7% loss in effective area. Although this is the preferred method, to get a feel of the systematic errors involved, we also include some analysis of the same observations but with spectra extracted using the constant rise-time rejection method. Compared with the statistical uncertainties, the measured ^{44}Sc flux does not depend much on the method chosen, but statistical errors are slightly larger for spectra that were extracted using the constant rise-time method (Table 1).

There exists a well-known error in the absolute flux density

[5] The observational identification numbers for the additional archival data used for our analysis are 30011001, 30011002, and 30795005. They were chosen on the availability of spectra made with the variable rise-time rejection method.

TABLE 1
Summary of Spectral Model Fits

Rise-Time Method	Model	Spectral Range (keV)	^{44}Sc Flux[a]	Power-Law Index	Power-Law Norm at 1 keV (photons s^{-1} keV^{-1})	Radio Index	Roll-off Energy (keV)	Emission Measure[b] ($\times 10^{12}$ cm^{-5})	χ^2/ν
Variable ……	Power law	12–300	2.1 ± 0.7	3.30 ± 0.05	2.3 ± 0.3	…	…	…	69.5/63
	Power law + thermal	12–300	1.0 ± 0.7	2.71 ± 0.06	0.28 ± 0.05	…	…	9.25 (fixed)[c]	96.7/63
	Power law + thermal	12–300	2.0 ± 0.7	3.2 ± 0.2	1.8 ± 0.8	…	…	1.3 (<4.5)	69.4/62
	SRESC + thermal	12–300	3.2 ± 0.8	…	…	0.85 (>0.848)[d]	9.2 ± 0.3	9.25 (fixed)[c]	120.8/63
	SRESC + thermal	12–300	2.8 ± 0.9	…	…	0.85 (>0.838)[d]	10 ± 1	5.8 ± 0.9	75.9/62
	Power law	30–100	1.9 ± 0.9	3.1 ± 0.4	$0.9^{+3.6}_{-0.7}$	…	…	…	15.6/20
	Power law + thermal	30–100	1.8 ± 0.9	3.0 ± 0.04	$0.7^{+2.8}_{-0.6}$	…	…	9.25 (fixed)[c]	15.5/20
Constant ……	Power law	12–300	2.5 ± 0.8	3.33 ± 0.06	2.5 ± 0.4	…	…	…	74.5/63
	Power law	30–100	1.7 ± 1.0	2.8 ± 0.5	$0.30^{+1.51}_{-0.24}$	…	…	…	18.7/20

Note.—All spectral models can be found in X-ray spectral analysis package XSPEC v.11 (Arnaud 1996). The first column indicates which background rejection criterium was used to obtain the source spectrum (see text). The ^{44}Sc lines were modeled by two delta lines with energies fixed at 67.9 and 78.4 keV and equal line flux. We used VMEKAL (a collisional equilibrium model) for the thermal component (Mewe, Kaastra, & Liedahl 1995). The SRESC model is described in Reynolds & Keohane 1999; it gives the synchrotron emission from a relativistic power-law distribution of particles with an exponential cutoff. Errors are statistical errors and correspond to 90% confidence intervals.

[a] In units of 10^{-5} photons cm^{-2} s^{-1}.

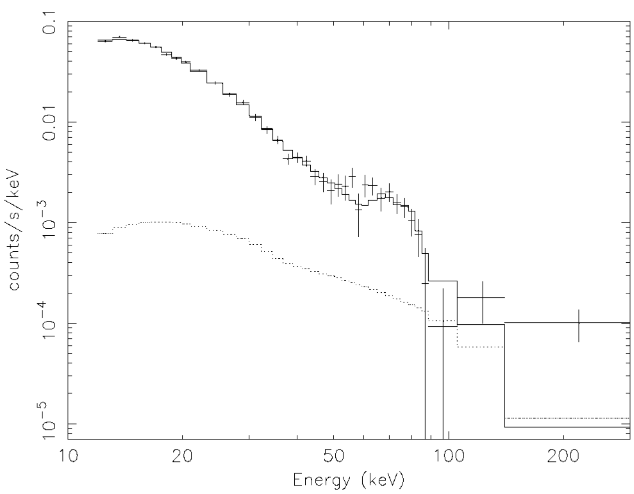
[b] The emission measure is defined as $n_H n_e V/4\pi d^2$. Note that in order to keep in line with models used by Vink et al. 1996, 2000 and Favata et al. 1997, we used a plasma enhanced in helium and nitrogen by a factor of 10 (based on optical observations of the shocked circumstellar medium; e.g., Chevalier & Kirshner 1979). The electron temperature was fixed to $kT_e = 4.2$ keV (Vink et al. 2000). Note that the ejecta is most likely the main source of thermal X-ray emission in Cas A, and so an O-rich composition could also be a reasonable model. This would not, however, make any difference to the shape of the thermal continuum at photon energies relevant here.

[c] The fixed emission measure is identical to that used by Vink et al. 2000; comparing with *ASCA*/SIS0 and *BeppoSAX*/MECS data shows that this implies that below 10 keV about half of the continuum is thermal, whereas the other half comes from an additional component.

[d] We allowed the radio spectral index, nominally 0.77 for Cas A, to vary in the range 0.7–0.85; the normalization parameter is the radio flux density at 1 GHz, which was fixed to 2720 Jy (D. A. Green 2000, A Catalogue of Galactic Supernova Remnants, 2000 August version; available at http://www.mrao.cam.ac.uk/surveys/snrs). The parameters derived from this model should be treated with caution, as the values for radio index and roll-off energy are highly correlated.

scale of the PDS instrument of a factor 0.86 ± 0.03. We took this factor and the 7% effective area loss into account by multiplying the response matrix by a factor of 0.80. Although the statistical error of the flux calibration is small, there exists some scatter in this relation (Fiore et al. 1999). In view of this, and the small differences between measurements made using the two rise-time rejection methods, we adopt a conservative 10% systematic error. In order to obtain reliable χ^2 statistics, the spectra were rebinned to channel widths of approximately $\Delta E/3$, where ΔE is the FWHM energy resolution, which is about 9 keV at 75 keV. Further rebinning was not necessary as the data are background-dominated, resulting in Gaussian error distributions for each channel. We verified that the spectra of each collimator were consistent with the best-fit model to the overall spectrum (see below). Similarly, we verified the consistency of the recently observed spectra and the archival spectra.

As far as we know, there are no instrumental background lines coinciding in energy with the ^{44}Sc lines. Possible contamination sources of line emission close to the ^{44}Sc lines are tantalum from the collimator and the onboard ^{241}Am calibration source; ^{241}Am emits photons at 60 keV, whereas the Ta Kα and Kβ transitions are at 57 and 65 keV with an emission ratio of 4 : 1. These lines may be responsible for a small emission excess around 60 keV (Fig. 1). However, adding these lines to our models changed the measured ^{44}Sc line flux with less than 5%: much smaller than the statistical uncertainty in the line flux.



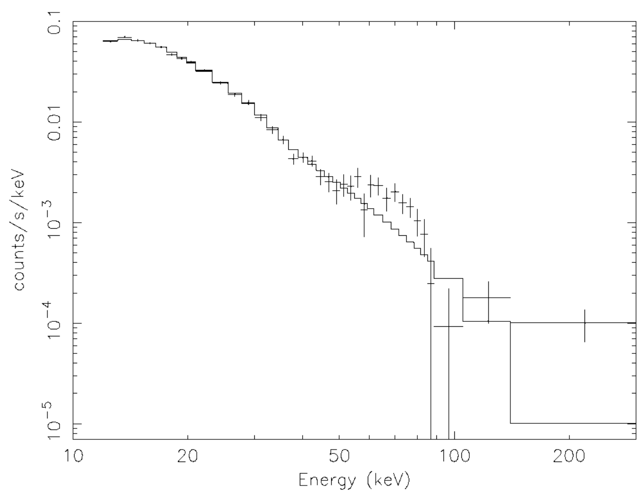


Fig. 1.—*BeppoSAX*/PDS spectrum of Cassiopeia A. The solid line in the left panel shows the spectral model including the ^{44}Sc lines at 68.9 and 78.4 keV. The dotted line shows the expected systematic error in the background subtraction, as estimated from blank-field PDS spectra (Guainazzi & Matteuzzi 1997). The right panel shows the best-fit power-law model without ^{44}Sc lines. The channels above 80 keV have been rebinned for presentational purposes.

Note that the observed power-law normalization of the PDS spectrum agrees with that of the *RXTE*/HEXTE (Allen et al. 1997). At 15.9 keV, their model fits imply 2.6×10^{-4} photons s^{-1} keV^{-1}, whereas the PDS spectrum indicates 2.5×10^{-4} photons s^{-1} keV^{-1}. The photon index above 16 keV of the *RXTE*/HEXTE spectrum, 3.04 ± 0.15, agrees within 1.6 σ with the value reported below. The continuum normalization also agrees within 1.5 σ with measurements by *CGRO*/OSSE (The et al. 1996), which measured a flux density of $(9.0 \pm 2.1) \times 10^{-7}$ photons cm^{-2} keV^{-1} at 100 keV, compared to $(5.8 \pm 0.8) \times 10^{-7}$ photons cm^{-2} keV^{-1} for our measurement, obtained from extrapolating the power-law normalization to 100 keV (Table 1, first row). Note that the *CGRO*/OSSE had a much larger field of view (11° × 4°.4) than the *BeppoSAX*/PDS.

3. DATA ANALYSIS

We present the combined PDS spectrum and the simplest possible model, consisting of a power-law continuum and two nuclear decay lines, in Figure 1. For this modeling of the continuum shape, the ^{44}Sc lines are detected with a significance of more than 5 σ ($\Delta\chi^2 = 30$). The flux in each line is $(2.1 \pm 0.7) \times 10^{-5}$ photons cm^{-2} s^{-1} and the photon index is 3.3 (see Table 1 for details). However, the nature of the hard X-ray continuum is still under debate. It has been argued that it is synchrotron radiation from shock-accelerated electrons or, alternatively, that it is bremsstrahlung emission caused by a nonthermal tail to the thermal electron distribution (Asvarov et al. 1990; Allen et al. 1997; Favata et al. 1997; Bleeker et al. 2001). A more specific bremsstrahlung model was worked out by Laming (2001a, 2001b), who calculated the spectrum of electrons accelerated by lower hybrid waves associated with shocks in the ejecta.

In this Letter, we limit ourselves to the detection of the ^{44}Sc lines. We therefore leave a detailed discussion of the hard X-ray continuum, which should also include data for the energy range 0.5–10 keV, to a future article. However, in order to test the dependence of the measured line flux estimates on the assumed continuum shape, we tested various continuum models, the results of which can be found in Table 1. It is surprising that the best fit to the PDS spectrum in a statistical sense is provided by a power-law model plus ^{44}Sc line emission. However, as the measured line flux depends on the continuum model chosen, we have to take the uncertainty about the nature of the continuum into account.

It is clear from spectral fits to the narrower 30–100 keV spectral range that the inclusion of a thermal component with $kT_e = 4.2$ keV has little effect on the estimated ^{44}Sc flux. Certainly, for this narrow range a power law is a reasonable approximation for the continuum. As the energy range is smaller, there is more statistical uncertainty about the photon index, and therefore the ^{44}Sc line flux is more uncertain. Indeed, the significance of the line emission drops from the 5 σ to the 3.4 σ level. The photon index versus line flux confidence contours for this energy range is shown in Figure 2. The 3 σ upper limit on the flux in both lines is 3.5×10^{-5} photons cm^{-2} s^{-1}, based on the 30–100 keV energy range. This upper limit is comparable to the ^{44}Ca line flux at 1157 keV recently obtained from *CGRO*/COMPTEL data, $(3.3 \pm 0.6) \times 10^{-5}$ photons cm^{-2} s^{-1} (68% confidence range; see Iyudin 1997). However, both measurements are consistent given the 25% systematic uncertainties for the COMPTEL measurement (Dupraz et al. 1997).

Although it is difficult to combine the COMPTEL and the PDS results, due to the unknown nature of the systematic errors, the fact that there are now two independent measurements of line emission associated with the ^{44}Ti decay increases the credibility of the detections. We therefore suggest adopting a ^{44}Sc/^{44}Ca line flux for Cas A of $(2.5 \pm 1.0) \times 10^{-5}$ photons cm^{-2} s^{-1}, which is consistent with both the PDS and COMPTEL measurements.

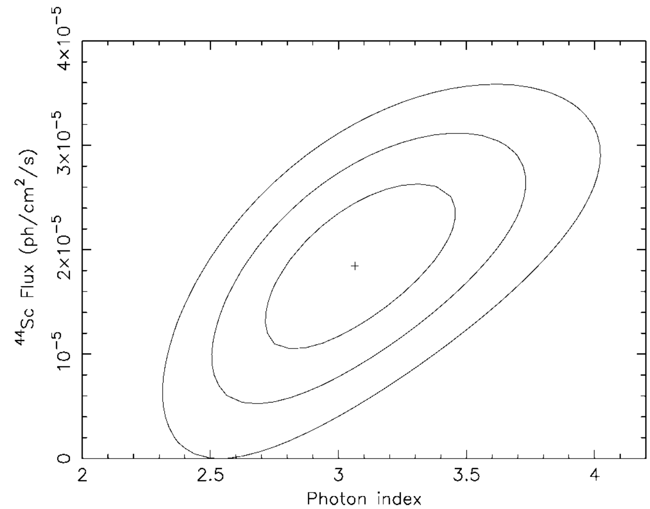


FIG. 2.—Confidence ellipses for the combination of power-law index and ^{44}Sc flux for the spectral energy range of 30–100 keV. The contours are 1 σ, 2 σ, and 3 σ two-parameter confidence levels ($\Delta\chi^2 = 2.3$, 6.17, and 11.8; see Lampton, Margon, & Bowyer 1976).

4. CONCLUSIONS

Since the initial discovery of the ^{44}Ca nuclear decay lines by *CGRO*/COMPTEL (Iyudin et al. 1994), our knowledge of the formation and decay of ^{44}Ti has substantially improved. Recently, the decay time of ^{44}Ti has been accurately measured to be 85.4 ± 0.9 yr by three independent experiments (Ahmad et al. 1998; Görres et al. 1998; Norman et al. 1998). As the Cas A supernova was probably observed by the English astronomer J. Flamsteed in 1680 (Ashworth 1980), the age of Cas A is ~320 yr. A good alternative is to use the kinematic age of the fast-moving optical knots, 330 yr (Thorstensen, Fesen, & van den Bergh 2001), but the age difference is so small that it has little effect on the inferred range of initial ^{44}Ti mass. The line flux of $(2.5 \pm 1.0) \times 10^{-5}$ photons cm^{-2} s^{-1}, combined with the ^{44}Ti decay time and a distance to Cas A of $3.4^{+0.3}_{-0.1}$ kpc (Reed et al. 1995), yields an initial ^{44}Ti mass in the range $(0.8–2.5) \times 10^{-4}$ $M_\odot$, with 1.2×10^{-4} $M_\odot$ corresponding to the adopted ^{44}Sc/^{44}Ca flux and distance to Cas A.

This is rather high compared to model predictions, which usually indicate ^{44}Ti masses below 10^{-4} $M_\odot$, except for progenitor masses around 12 $M_\odot$ and above ~25 $M_\odot$ (Timmes et al. 1996). For that reason, Mochizuki et al. (1999) made the interesting suggestion that the ^{44}Ti decay may be delayed, as a result of complete ionization of ^{44}Ti, inhibiting the decay of ^{44}Ti by the capture of a K-shell electron. However, recently Laming (2001c) showed that the electron temperature in the ejecta was probably never high enough to seriously affect the ^{44}Ti decay.

The production of ^{44}Ti increases with the size of the helium core of the progenitor, but material falling back on the neutron star or black hole limits the amount of ejected ^{44}Ti. Model calculations show that massive stars have more fallback, but presupernova wind loss may limit the amount of material falling back (Timmes et al. 1996). This agrees with the idea that the progenitor of Cas A was a not too massive (~30 $M_{\odot}$) Wolf-Rayet star that suffered heavy mass loss (Vink, Kaastra, & Bleeker 1996). In addition, asymmetries in the explosion may have increased the amount of ^{44}Ti synthesized (Nagataki et al. 1998). The likely presence of a neutron star (Chakrabarty et al. 2001) in Cas A further constrains the explosion scenario for Cas A, as too much fallback would have resulted in the formation of a black hole.

Although we have now finally detected the ^{44}Sc nuclear decay lines at 67.9 and 78.4 keV, interesting observations remain to be done with future hard X-ray and gamma-ray missions. The solid-state detectors on board the *International Gamma-Ray Astrophysical Laboratory* will be able to measure the line broadening of the ^{44}Ca line accurately and constrain the properties of the hard X-ray continuum further. In addition, hard X-ray experiments using multilayer mirrors will be able to map the spatial distribution of ^{44}Ti in Cas A on the arcminute scale.

Support for this work was provided by NASA through *Chandra* Postdoctoral Fellowship Award PF0-10011 issued by the *Chandra X-Ray Observatory* Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-39073. J. M. L. was supported by basic research funds of the Office of Naval Research. This research has made use of SAXDAS linearized and cleaned event files (Rev.2.1.4) produced at the *BeppoSAX* Science Data Center.

REFERENCES

Ahmad, I., Bonino, G., Cini Castagnoli, G., Fischer, S. M., Kutschera, W., & Paul, M. 1998, Phys. Rev. Lett., 80, 2550

Allen, G. E., et al. 1997, ApJ, 487, L97

Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. Jacoby & J. Barnes (San Francisco: ASP), 17

Ashworth, W. B. 1980, J. Hist. Astron., 11, 1

Asvarov, A. I., Dogiel, V. A., Guseinov, O. H., & Kasumov, F. K. 1990, A&A, 229, 196

Bleeker, J., Willingale, R., van der Heyden, K., Dennerl, K., Kaastra, J., Aschenbach, B., & Vink, J. 2001, A&A, 365, L225

Chakrabarty, D., Pivovaroff, M. J., Hernquist, L. E., Heyl, J. S., & Narayan, R. 2001, ApJ, 548, 800

Chevalier, R. A., & Kirshner, R. P. 1979, ApJ, 233, 154

Diehl, R., & Timmes, F. X. 1998, PASP, 110, 637

Dupraz, C., et al. 1997, A&A, 324, 683

Favata, F., et al. 1997, A&A, 324, L49

Fiore, F., Guainazzi, M., & Grandi, P. 1999, Handbook for *BeppoSAX* NFI Spectral Analysis (Rome: *BeppoSAX* Science Data Center)

Frontera, F., et al. 1997, A&AS, 122, 357

Görres, J., et al. 1998, Phys. Rev. Lett., 80, 2554

Guainazzi, M., & Matteuzzi, A. 1997, *BeppoSAX* Science Data Center Tech. Rep. TR-011

Iyudin, A. F. 1997, Nucl. Phys. A, 654, 900c

Iyudin, A. F., et al. 1994, A&A, 284, L1

Laming, J. M. 2001a, ApJ, 546, 1149

———. 2001b, ApJ, in press (astro-ph/0108285)

———. 2001c, in Proc. Joint *SOHO-ACE* Workshop 2001: Solar and Galactic Composition, ed. R. F. Wimmer-Schweingruber (New York: AIP), in press (astro-ph/0108316)

Lampton, M., Margon, B., & Bowyer, S. 1976, ApJ, 208, 177

Mewe, R., Kaastra, J. S., & Liedahl, D. A. 1995, Legacy, 6, 16

Mochizuki, Y., Takahashi, K., Janka, H. T., Hillebrandt, W., & Diehl, R. 1999, A&A, 346, 831

Nagataki, S., Hashimoto, M., Sato, K., Yamada, S., & Mochizuki, Y. S. 1998, ApJ, 492, L45

Norman, E. B., et al. 1998, Phys. Rev. C, 57, 2010

Reed, J. E., Hester, J. J., Fabian, A. C., & Winkler, P. F. 1995, ApJ, 440, 706

Reynolds, S. P., & Keohane, J. W. 1999, ApJ, 525, 368

Rothschild, R. E., et al. 1997, Nucl. Phys. B, 69, 68

The, L.-S., et al. 1996, A&AS, 120, 357

Thorstensen, J. R., Fesen, R. A., & van den Bergh, S. 2001, AJ, 122, 297

Timmes, F. X., Woosley, S. E., Hartmann, D. H., & Hoffman, R. D. 1996, ApJ, 464, 332

Vink, J., Kaastra, J., & Bleeker, J. 1996, A&A, 307, L41

Vink, J., Kaastra, J., Bleeker, J., & Bloemen, H. 2000, Adv. Space Res., 25, 689