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X-Ray Spectroscopic Laboratory Experiments in Support of the NASA X-Ray Astronomy Flight Program

Progress Report
1997

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Introduction

During the 1997 performance period, our work focused on the L-shell X-ray emission from highly charged iron ions in the 10 – 18 Å region. Details of our accomplishments in 1997 are presented in the following. We start by describing the laboratory measurements made and their impact on the X-ray flight program and conclude by an overview of new instrumental capabilities developed for uses in the coming year.

1. Physics Results

In astronomical plasmas, transitions in Fe XVII to Fe XXIV of the type $n \geq 3 \rightarrow n = 2$ are one of the dominant forms line emission in the 6 Å to 18 Å spectral region. Spectra from the *Advanced Satellite for Cosmology and Astrophysics (ASCA)* exhibit discrepancies with the relative line intensities of various Fe XXIII and XXIV L-shell emission lines predicted by standard plasma emission codes. Distorted-wave calculations of Fe XXIII and Fe XXIV electron impact excitation rate coefficients by Liedahl, Osterheld, & Goldstein (1995, Ap.J., 438, L115) appear to provide better agreement with the *ASCA* data. Using the Lawrence Livermore electron beam ion trap (EBIT) we had measured in 1996 (Savin *et al.*, Ap.J., 470, L73) the relative line emission of several Fe XXIV $3 \rightarrow 2$ and $4 \rightarrow 2$ lines at electron energies significantly greater than the excitation threshold energies of the lines observed and found good agreement with the calculations of Liedahl *et al.* The calculations of Liedahl *et al.*, however, do not include the effects of resonant excitation (RE). They do account for the resonant process dielectronic recombination (DR). DR is, however, incompletely accounted for by the standard plasma emission codes and RE not at all. DR and RE are important at electron energies near threshold, i.e., typically at temperatures near the peak of the ion abundance making these processes very important. Using EBIT, we measured in 1997 the RE and DR contributions to Fe XXIV $3 \rightarrow 2$ line emission at energies around threshold. We found that at electron temperatures near the Fe XXIV peak emissivity DR enhances the line emissivity by $\sim 20\%$ and RE by $\sim 10\%$. Our results indicate the data used by the standard plasma emission codes can underestimate line emissivities by at least $\sim 30\%$. The initial results of this work were presented at the *International Conference on Atomic and Molecular Data and Their Applications (Gaithersburg, MD, September 1997)* [1] and a paper for ApJ is in preparation.

The Fe XVII L-shell emission represents another diagnostically important spectrum in X-ray astronomy and astrophysics research. In 1997 we completed a comprehensive study of the Fe XVII L-shell spectrum on the Livermore EBIT. A comprehensive line identification and wavelength measurement of the Fe XVII L-shell emission between 9.8 Å and 17.5 Å revealed twice as many lines as previously observed and catalogued. Most importantly, we identified transitions from n=3 to n=11 of the type $n\ell$-$2p$, where ℓ = s, d and p. These lines fall into the narrow wavelength region from about 10.0 to 10.5 Å. In plasma sources these lines are blended with lines from other elements or charge states and therefore had never been resolved and measured. We also measured their intensity and found them to be as strong as 13% of the intensity of the strongest L-shell Fe XVII line. This means that although each individual line is weak, their sum represents a considerable flux that must be included in the emission codes. Indeed, new models that include the flux of these lines provide significant improvements in fitting *ASCA* L-shell spectra. A paper has been submitted to ApJ [2] and will appear in the summer of 1998.

Our 1997 Fe XVII measurements have also provided a definitive value of the 2p-3d resonance and intercombination line ratio. This ratio has been proposed and used as a density diagnostic for stellar atmoshperes because it is thought to be sensitive to resonant scattering. The problem with using the line ratio for this purpose it that theory cannot agree on its value even in the absence of resonant scattering. Over twenty calculations have been made in as many years resulting in values ranging from 2.5 to 4.5. Our 1997 measurements have provided a value of 3.04 ± 0.12. Our measurement allows the use of the line ratio for diagnostic purposes with greatly improved confidence. These result are reported in [2]. The same ratio was also studied in neighboring ions, and systematic differences with theory were found. These differences point the way for improved theoretical treatments of the L-shell lines. The results are being prepared for publication.

In 1997 we have also completed our analysis of the spectra of highly ionized iron species between 7 and 9 Å obtained at the Princeton Large Torus tokamak under plasma conditions similar to those present in stellar flares. The wavelengths of many iron lines are measured with very high accuracy ($\lambda/\Delta\lambda$ up to 40,000). Theoretical spectra that predict both the wavelength and intensity of Fe emission lines were compared with the observed spectra and used to make accurate line identifications. Virtually all the observed iron lines are found to arise from n = 4, 5, and 6 $\rightarrow$ 2 transitions in Fe XXI to Fe XXIV, and many lines are identified for the first time. Several transitions have been shown to have diagnostic applications, and a detailed analysis of the density sensitivity of Fe XXII lines has been carried out. In addition, a number of emission lines from heliumlike Mg XI and Al XII, which may be useful as plasma diagnostics, have been observed in the 7 – 9 Å wavelength range. We have found that some of the more important Mg XI and Al XII lines are, in fact, blended with lines from Fe XXII, XXIII, and XXIV. These previously unknown blends will need to be taken into account when attempting to use these Mg and Al lines as plasma diagnostics. A paper reporting these results has been submitted to ApJ [3] and will appear in July 1998.

During the 1997 performance period, we have furthermore experimentally demonstrated the importance of fine-structure core excitations for dielectronic recombination (DR) in photoionized gas. At the low electron temperatures existing in photoionized gases with cosmic abundances, DR proceeds primarily via $n\ell_j \rightarrow n\ell'_{j'}$ excitations of core electrons ($\Delta n = 0$ DR). At these temperatures, the dominant DR channel often involves $2p_{1/2} \rightarrow 2p_{3/2}$ fine-structure core excitations, which are not included in LS-coupling calculations or the Burgess formula. Using the heavy-ion storage ring at the Max-Planck-Institut für Kernphysik in Heidelberg, Germany, we have verified experimentally for Fe XVIII that DR proceeding via this channel can be significant in relation to other recombination rates, especially at the low temperatures characteristic of photoionized gases. At temperatures in photoionized gases near where Fe XVIII peaks in fractional abundance, our measured Fe XVIII to Fe XVII $\Delta n = 0$ DR rate coefficient is a factor of ~ 2 larger than predicted by existing theoretical calculations. We have carried out new fully-relativistic calculations using intermediate-coupling which include the $2p_{1/2} \rightarrow 2p_{3/2}$ channel and agree to within $\sim 30\%$ with our measurements.

DR via the $2p_{1/2} \rightarrow 2p_{3/2}$ channel may also have spectroscopic implications, providing unique spectral signatures at soft X-ray wavelengths which could provide good electron temperature diagnostics. These results were reported in ApJ [4]. A second paper will be published in the proceedings of the *International Conference on Atomic and Molecular Data and Their Applications (Gaithersburg, MD, September 1997)* [5].

2. Instrument Development

During the performance period we have constructed and successfully implemented a set of two broadband X-ray spectrometers at the Livermore electron beam ion source to observe the full wavelength band (10–18 Å) simultaneously. Previously, a total of nine overlapping spectrometer settings were required to cover the L-shell emission of iron in this region. The new instruments thus represent a major advance, which will be very useful in our continuing studies.

We have also completed the implementation of a new capability to simulate a Maxwell-Boltzmann electron energy distribution. The production of a quasi-Maxwellian plasma was accomplished by sweeping in time both the electron beam energy and electron gun anode voltage. Because the electron beam current varies as $n_e E^{1/2}$, we must also sweep the anode (extraction) voltage of the electron gun in EBIT synchronously with the beam energy, so as to vary the current in such a way as to keep the electron density nearly constant. We have characterized the quasi-Maxwellian and found it to be an excellent simulator of a Maxwellian plasma. The advantage of this technique over other plasma sources is that we can make full use of a well characterized laboratory source that now automatically provides rate coefficients in addition to cross sections. In other words, we can "dial up" the temperature of interest, density and temperature gradients are absent, and we can still control the excitation processes and choose the ionization balance. Like the new broadband spectrometers, the quasi-Maxwellian plasma capability will find increasing uses in the study of the iron L-shell X-ray emission in the coming year.

Papers submitted for Publication in 1997

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[3] Wargelin, B. J., Beiersdorfer, P., Liedahl, D. A., Kahn, S. M., and von Goeler S. 1998, "Observation and Modeling of High-n Iron L-Shell Lines from Intermediate Ion Stages," *Ap.J.* (accepted).

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[5] Savin, D. W., Bartsch, T., Chen, M. H., Kahn, S. M., Liedahl, D. A., Linkemann, J., Müller, A., Schippers, S., Schmitt, M., Schwalm, D., and Wolf, A. 1998, "New Electron Temperature and Density Diagnositics for Photoionized Gas," in *NIST Special Publications 926, International Conference on Atomic and Molecular Data - Contributed Papers, W. L. Wiese and P. J. Mohr, eds. (Gaithersburg, MD).*