New Electron Temperature and Density Diagnostics for Photoionized Gas

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The ionization and heating of the media surrounding accretion-powered compact sources, such as cataclysmic variables, X-ray binaries, and active galactic nuclei, is dominated by photoionization. Theoretical models of photoionized gases show that the ionization structure is determined by photoionization balanced by radiative recombination (RR) and dielectronic recombination (DR). The electron temperature at which the fractional abundance of a given ion peaks [1] is far below the temperature where the ion would exist in coronal equilibrium [2,3]. As a result, X-ray line emission is produced by RR and DR and not by electron impact excitation [1,4]. Also, the radiative recombination continuum (RRC) of an ion is predicted to appear as a distinct narrow feature just above the ionization threshold of the ion [5].

With the improved spectral resolution offered by the SIS detectors of *ASCA* [6] it has become possible to observe some of these unique properties of photoionized gases. From *ASCA* observations, the RRC for Ne X has been identified in SIS spectra of the low-mass X-ray pulsar 4U 1626-67 [7] and the Mg XII, Si XIV, and S XVI RRC have been identified in spectra of the X-ray binary Cygnus X-3 [8]. From the widths of the RRC features, electron temperatures of ~5-100 eV are inferred for the X ray emission line regions. As predicted, these temperatures are far below the temperatures where these ions are formed in coronal equilibrium.

The upcoming launches of the X-ray astronomy satellites *AXAF*, *XMM*, *Spectrum-Röntgen Gamma*, and *Astro-E* are expected to open a new era in the spectroscopy of extrasolar X-ray sources. The combination of the large collecting area telescopes and high resolution spectrometers on these satellites will produce high quality spectra to which a wide range of plasma diagnostic techniques will be applied. Of particular interest will be the 0.7-2.0 keV (6-18 Å) spectral band which is dominated by the *L*-shell transitions (*i.e.* $n \geq 3 \rightarrow n = 2$) of Fe XVII to Fe XXIV (the iron *L*-shell ions). These ions exist over a wide range of conditions and are expected to provide many valuable plasma diagnostics.

L-shell iron forms at the same conditions where Ne X, Mg XII, Si XIV, and S XVI form. Thus, the temperatures measured in 4U 1626-67 and Cyg X-3 largely validate the predicted temperature range for *L*-shell iron. However, the exact temperature at which a given ion forms depends on many variables, such as the metallicity of the gas, the shape of the ionizing spectrum, the presence of additional heating and/or cooling mechanisms, and radiative transfer effects. These can be expected to vary for different sources. For most iron *L*-shell ions at these low temperatures, DR via $\Delta n = 0$ core excitations dominates recombination. It is therefore important

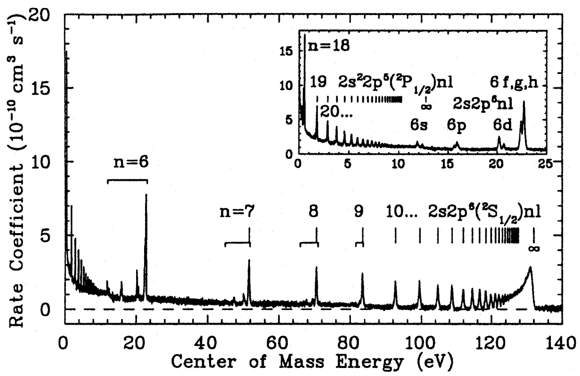

Figure 1: Measured Fe XVIII to Fe XVII recombination rate coefficient versus collision energy. The nonresonant "background" is due to RR.

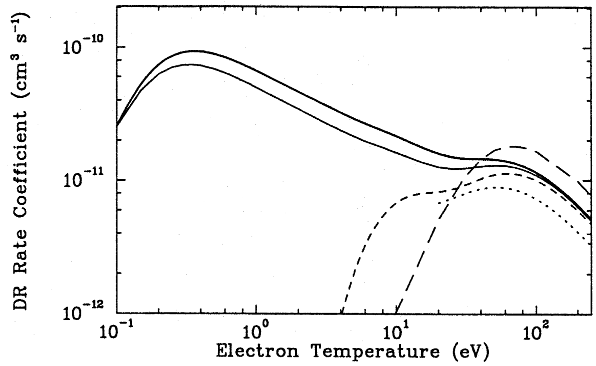

Figure 2: Fe XVIII to Fe XVII Maxwellian averaged $\Delta n = 0$ DR rate coefficients. See text for explanation.

that the iron L-shell DR rates be benchmarked over a range which encompasses the predicted temperature range.

To address the needs for modeling photoionized gases, we have initiated a series of experiments to measure the $\Delta n = 0$ DR rates for the iron L-shell ions. Measurements are carried out using the heavy-ion Test Storage Ring (TSR) at the Max-Planck-Institut für Kernphysik in Heidelberg, Germany [9]. Here we present our results for $\Delta n = 0$ DR of Fe XVIII [10]. In particular we have investigated the capture channels

$$\mathrm{Fe}^{17+}(2s^2 2p^5[^2P_{3/2}]) + e^- \rightarrow \begin{cases} \mathrm{Fe}^{16+}(2s^2 2p^5[^2P_{1/2}]nl) & (n = 18, \ldots, \infty) \\ \mathrm{Fe}^{16+}(2s 2p^6[^2S_{1/2}]nl) & (n = 6, \ldots, \infty). \end{cases} \qquad (1)$$

The radiative stabilization of these autoionizing states to bound configurations of Fe XVII leads to DR resonances for collision energies between 0 and 132 eV.

Fig. 1 shows the measured Fe XVIII DR resonances. We have integrated the measured DR resonance strengths and energies with a Maxwellian electron velocity distribution to yield a total Fe XVIII $\Delta n = 0$ DR rate coefficient as a function of electron temperature (Fig. 2, upper solid line). Various theoretical DR rates are also shown in Fig. 2. At $k_B T_e \sim 15$ eV, near where Fe XVIII is predicted to peak in fractional abundance in photoionized gases, our inferred DR rate is a factor of ~2 larger than the calculations of Ref. [11] (long dashed line), Ref. [12] (dotted line), and Ref. [13] (short dashed line). These theoretical rates all tend rapidly to zero at $k_B T_e < 20$ eV because they have not included DR via $2p_{1/2} \rightarrow 2p_{3/2}$ core excitations. The calculations of Ref. [11] and Ref. [13] used LS-coupling and thus do not include fine-structure core excitations. The calculations of Ref. [12] used intermediate-coupling which can account for fine structure; but that work did not include the $2p_{1/2} \rightarrow 2p_{3/2}$ channel because the calculations were carried out for the high temperatures of collisionally ionized plasmas (where this channel is unimportant). Also shown in Fig. 2 are our new calculations [10] which include the $2p_{1/2} \rightarrow 2p_{3/2}$ channel (lower solid line). Our new calculations agree to within ~30% with our measurements.

The commonly used models of photoionized gas incorporate DR rates which have been calculated using either the Burgess formula [14] or LS-coupling. The Burgess formula is known to be inappropriated for low temperatures [15]. And as we have shown, LS-coupling calculations do not properly account for all possible DR channels at low temperatures where DR can proceed

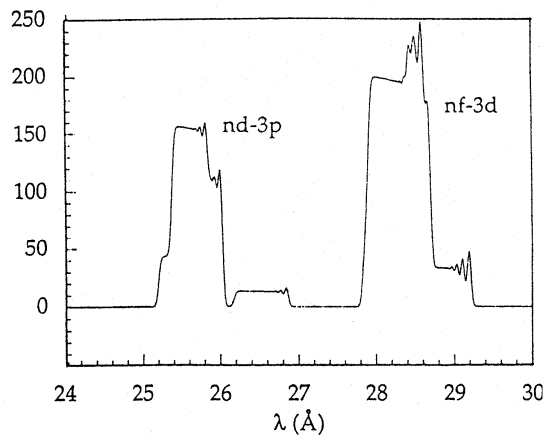

Figure 3: Preliminary calculations of the Fe XVII soft X-ray spectrum produced by Fe XVIII DR via $2p_{1/2} \rightarrow 2p_{3/2}$ core excitations. The intensity (ordinate) is in arbitrary units. The $nd \rightarrow 3p$ and $nf \rightarrow 3d$ transition arrays are shown for $18 \leq n \leq 100$.

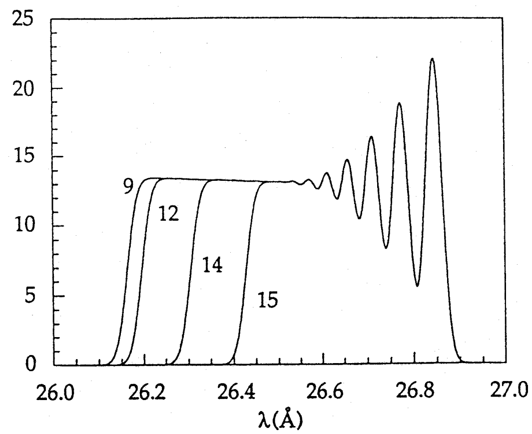

Figure 4: Preliminary calculations of the electron density dependence of the Fe XVII $nd \rightarrow 3p$ transition array produced by Fe XVIII DR via $2p_{1/2} \rightarrow 2p_{3/2}$ core excitations. The transition array is shown for $\log n_e$ = 9, *12*, 14, and 15 cm^{-3}. The intensity (ordinate) is in arbitrary units.

primarily via $nl_j \rightarrow nl'_{j'}$ excitations of core electrons. A re-evaluation of the recommended low temperature DR rates is needed to assess for what *L*-shell and *M*-shell ions new rates must be determined.

L-shell iron $\Delta n = 0$ DR via $2s \rightarrow 2p$ core excitations has been proposed as a possible electron temperature diagnostic for photoionized gas [16,17]. Here dielectronic capture proceeds via a $[2s^2 2p^k + e^- \rightarrow 2s2p^{k+1}nl]$ channel. Stabilization typically proceeds via a $2p \rightarrow 2s$ radiative decay. However, for low enough n, the $2s^{-1}$ core can "freeze", and the outer electron radiatively cascade to the *L*-shell, filling the $2s^{-1}$ hole. These cascades occur in the presence of an excited $2p$ electron. In the low density limit, the resulting spectrum is unique to the DR process. Thus, as the temperature dependence of RR and DR is different, the ratio of lines produced by RR and DR provide the makings of a temperature diagnostic. Developing these diagnostics requires accurate knowledge of the DR resonance energies and strengths, which can be provided by measurements such as those presented here.

Here we propose a new electron temperature and density diagnostic for photoionized gas which is based on DR via a $2p_{1/2} \rightarrow 2p_{3/2}$ core excitation. Because the $2p_{3/2} \rightarrow 2p_{1/2}$ radiative transition is electric-dipole forbidden, DR via this channel stabilizes by a radiative decay of the captured electron. The energy of the $2p_{1/2} \rightarrow 2p_{3/2}$ transition is ~15 eV, and the recombining electrons are captured into high n levels. For Fe XVIII, we find $n \geq 18$. These high-lying electrons have a high branching ratio for undergoing an $n \rightarrow 3$ transition and producing soft X-rays. Fig. *3* shows a preliminary calculated soft X-ray spectrum resulting from Fe XVIII $\Delta n = 0$ DR via $2p_{1/2} \rightarrow 2p_{3/2}$ core excitations. The resolution is $\Delta\lambda = 0.07$ Å which is comparable to that planned for the spectrometers of AXAF and *XMM*. The broad features are due to unresolved $n \rightarrow 3$ transitions. The high energy sides of these transition arrays are due to very high n levels. These weakly-bound levels can be collisionally ionized before they radiatively decay. The highest bound n level is a function of the electron density n_e. Thus the widths of these transition arrays are sensitive to n_e and can be used to infer the density of the radiating gas. Fig. 4 shows the density sensitivity for one of the $nd \rightarrow 3p$ transition arrays shown in Fig. 3. Further experimental and theoretical work is in progress to explore this new class of temperature diagnostics.

Acknowledgments

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