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Laboratory Studies of the X-ray Emission Produced by the Interaction of Solar Wind Heavy Ions with Comets

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ABSTRACT

The process of X-ray emission following charge exchange between solar wind heavy ions and cometary gases is studied in the laboratory. The emission is recorded with the spare *ASTRO-E* 6x6 microcalorimeter array. The microcalorimeter affords a resolution of better than 10 eV in the range of X-ray energies of interest and thus individual emission lines can be resolved. Our present measurements focus on the most abundant K-shell heavy ions found in the solar wind. In particular, we measure the K-shell emission of bare C, N, O, and Ne, and their hydrogenlike counter parts interacting with such gases as CO₂, N₂, and CH₄. Several results are noted that had not been considered in the early cometary X-ray models.

1. Introduction

Charge exchange between cometary gases and solar wind heavy ions is likely to be the dominant process of X-ray emission from comets. While charge exchange cross sections have been measured by various facilities, little experimental data has been gathered about the detailed processes that lead to X-ray line formation. To fill this void, we are studying the charge exchange process in the laboratory.

Our measurements utilize ions from the EBIT-I and EBIT-II electron beam ion traps at the Lawrence Livermore National Laboratory (Levine et al. 1988). EBIT-I and EBIT-II are the first and second such devices put into operation in 1986 and 1990, respectively. Ions

are first produced with the electron beam on in the so-called electron trapping mode. Then the beam is turned off, and the device is operated in the so-called magnetic trapping mode (Beiersdorfer et al. 1996). In this mode, the trap is operated like a Penning trap. Neutral atomic or molecular gases of choice are introduced into the trap, and the ions are allowed to undergo charge exchange reactions.

The charge exchange induced X-ray emission is recorded with the spare *ASTRO-E* microcalorimeter array built at the Goddard Space Flight Center (Porter et al. 2000). This calorimeter has unique features that make charge-exchange measurements possible. First, it has a large effective area ($\approx 13 \text{ mm}^2$) consisting of 36 individual elements, 32 of which are active. A large area is necessary to observe the rather weak signal from charge exchange, which is about 100 – 1000 times weaker than x-ray emission from electron-impact excitation during the electron trapping mode. Second, the Goddard calorimeter gives a time-tag to each photon. This is necessary to distinguish between X rays collected during the electron trapping mode and the magnetic trapping mode. Third, the long-term gain stability allows us to collect data for extended periods without compromising the resolving power. Finally, the differential response of our instrumentation is calibrated *in situ*. This is necessary at the low energies of the X rays of interest ($< 1000 \text{ eV}$), where the instrumental response is strongly affected by the transmission of the thermal shielding foils.

2. Typical Results

Our present measurements focus on the X-ray emission from K-shell heavy ions. A spectrum of the X-ray emission from hydrogenlike Ne^{9+} following charge exchange between bare Ne^{10+} and neutral neon is shown in Fig. 1. The spectrum shows lines corresponding to transitions from the $2p$, $3p$, $4p$, $5p$, and $6p$ upper levels to the $1s$ ground state. These are labeled $\text{Ly}\alpha$, $\text{Ly}\beta$, $\text{Ly}\gamma$, $\text{Ly}\delta$, and $\text{Ly}\epsilon$, respectively.

The figure also shows the predictions of the cometary X-ray models developed by Häberli et al. (1996) and Wegmann et al. (1997). Häberli et al. included emission from only the $2p$ level. Wegmann et al. included emission from all upper levels accessible to population by charge exchange assuming that the amount of emission from each upper level is same for all.

A spectrum of the X-ray emission from heliumlike Ne^{8+} following charge exchange between hydrogenlike Ne^{9+} and neutral neon is shown in Fig. 2. The spectrum is very different from that shown in Fig. 1. First, emission involving high principal quantum numbers is suppressed. Most emission is from lines with an $n = 2$ upper level. Second, the forbidden transition $1s2s \ ^3S_1 \rightarrow 1s^2 \ ^1S_0$ produced the strongest X-ray emission. This emission pat-

tern is the direct result of the presence of triplet levels in the heliumlike ion, which strongly determines the radiative properties of the heliumlike ion (Beiersdorfer et al. 2001). Triplet levels do not exist in hydrogenlike ions.

Predictions from Häberli et al. (1996) and Wegmann et al. (1997) are again overlaid with the measured spectrum in Fig. 2.

3. Conclusion

Our measurements have produced several surprising results that had not been considered in the early cometary X-ray models. The emission pattern is different for different isoelectronic systems; the forbidden line $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$ produces the strongest emission in heliumlike ions. The actual emission pattern changes with the collision energy (Beiersdorfer et al. 2001). Moreover, the detailed emission depends on the chemical composition of the cometary gases.

The complexity of the X-ray emission from cometary (and presumably from planetary) atmospheres implies rich opportunities for using the emission for diagnostic purposes that go beyond merely determining the composition and intensity of the solar wind.

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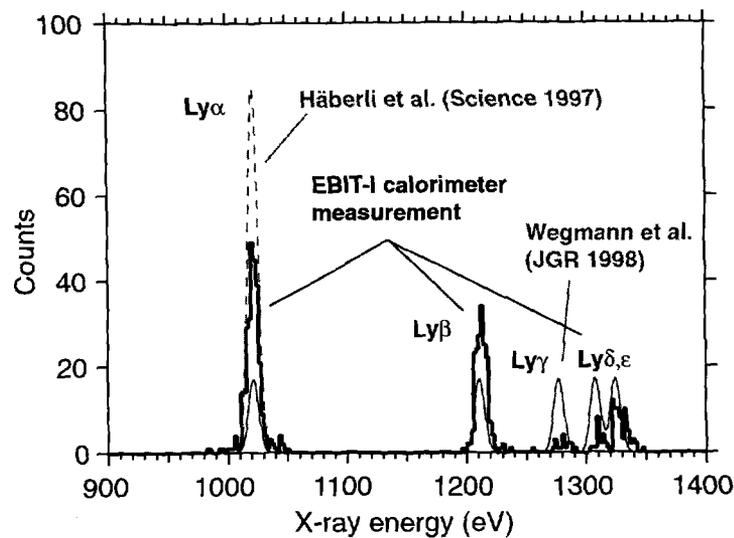


Fig. 1.— Ne IX spectrum measured with the Goddard X-ray microcalorimeter on the Livermore EBIT-II electron beam ion trap. The spectrum was produced by charge exchange recombination of Ne^{10+} with neutral neon.

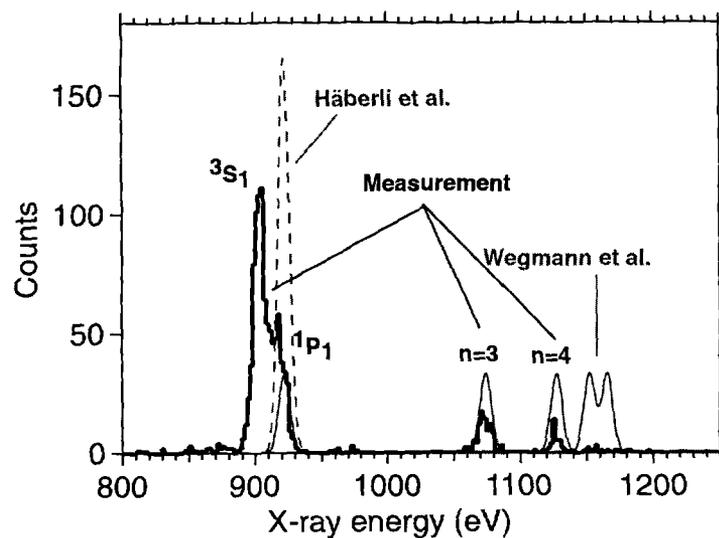


Fig. 2.— Ne VIII spectrum measured with the Goddard X-ray microcalorimeter on the Livermore EBIT-II electron beam ion trap. The spectrum was produced by charge exchange recombination of Ne^{9+} with neutral neon forming excited heliumlike Ne^{8+} ions.