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LABORATORY ASTROPHYSICS EXPERIMENTS IN X-RAY TRANSFER PHYSICS RELEVANT TO COSMIC ACCRETION-POWERED SOURCES

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Résumé. — L'interprétation des observations spectroscopiques des rayons cosmics X à basse energie nécessite un grand progrès dans nos connaissances en physique atomique et processus radiatifs, notamment pour la categorie des systèmes qui tirent leur energie de l'accretion comme les variables cataclysmiques, les binaires X et les noyaux actifs de galaxies. Pour de telles sources, on obtient des raies spectrales à courte longeur d'onde qui sont formées lors du transfert d'une radiation X d'une source centrale ènergetique vers un milieu extèrieur plus froid. Le gas responsable de l'émission est photoionisé et les populations des diffèrents niveaux sont gouvernées principalement par les cascades de recombination et la photoexcitation, les collisions ne jouant qu'un rôle nègligeable. De tels processus peuvent être assez complexes et plusieurs incertitudes demeurent. Nous dèveloppons une nouvelle approche de ce problème à l'aide de spectres résolus en temps de plasmas excités par des lasers. Les experiences que nous menons actuellement incluent la mesure: (a) des sections efficaces de photoabsorption dans les couches internes et externes pour des ions intermédiaires d'élements abondants, et (b) des processus de fluorescences resultant de la coincidence de longueurs d'onde de transitions resonnantes pour des ions differents. En relation avec ce programme, nous avons developpé un nouveau spectrometre à raiseau à reflection couplé à une "streak" camera qui fournit des spectres haute résolution dans les domaines rayons X à basse energie et UV extreme, au niveau subnanoseconde. Nous décrivons notre appareillage et quelques rèsultats préliminaires.

Abstract. — The interpretation of upcoming cosmic soft X-ray spectroscopic observations may require a vast improvement in the state of our knowledge of basic atomic physics and radiation transfer processes, particularly for the important class of accretion-powered systems such as cataclysmic variables, X-ray binaries, and active galactic nuclei. For these sources, short wavelength spectral features are formed in the transfer of X-radiation from a powerful central source outward through a cooler, surrounding medium. The line emitting gas is photoionized and the level populations are determined largely by recombination cascades and photoexcitation as opposed to collisional effects. These processes can be rather complex and many uncertainties remain. We are developing a new approach to this problem using time-resolved studies of laser produced plasmas. Experiments which are currently underway include the measurements of: (a) inner and outer shell photoabsorption cross-sections of intermediate ions of abundant elements, and (b) fluorescent excitation processes due to wavelength coincidences of resonant transitions from different ions. In connection with this program, we have developed a novel reflection grating spectrometer coupled to a streak camera which provides high resolution spectra at soft X-ray and EUV wavelengths at the sub-nanosecond level. We describe our laboratory facility and some of our preliminary experimental results.

1. Introduction.

Spectroscopy of cosmic sources at extreme ultraviolet and soft X-ray energies is generally considered to be one of the most promising and exciting frontiers of space astrophysics research. Included in these spectral bands are the prominent K-shell, L-shell, and M-shell transitions of most ions of virtually all abundant elements. Detection of emission and/or absorption features associated with such transitions can provide important diagnostics for physical conditions thought to be appropriate to a wide variety of astronomical objects. Because of the limiting sensitivity of previous or existing experiments, observations with near-adequate spectral resolution have, as yet, only been performed for the brightest cosmic sources. However, with the current development of high resolution spectroscopic instruments for the NASA Advanced X-Ray Astrophysics Facility (AXAF) and the European Space Agency's X-Ray Multi-Mirror Mission (XMM), this work will be extended considerably over the next decade. Increases in sensitivity by 2-3 orders of magnitude and increases in resolution by factors of 3-1000 are expected.

Of course, our ability to utilize such spectroscopic measurements to acquire information about cosmic sources depends not only on the quality of the data we can obtain, but also on our knowledge of basic atomic physics and radiation transfer processes that are important in shaping the spectrum. Uncertainties in this latter area will severely limit our interpretation of the spectra for a large class of astrophysical

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investigations. Cosmic sources which are expected to exhibit EUV/soft X-ray spectral features generally fall into two distinct categories: (a) hot, optically thin, thermal emitters (e.g. stellar coronae, supernova remnants), for which the line and continuum excitation is dominated by collisional effects and the deexcitation is dominated by spontaneous radiative decay [1]; and (b) X-ray photoionized nebulae (e.g. cataclysmic variables, X-ray binaries, active galactic nuclei), in which spectral features are formed in the transfer of X-radiation from a powerful central source outward through a cooler, surrounding medium. For the first category, accurate modeling of the emitted spectra only requires accurate knowledge of the various collisional rates and of the oscillator strengths appropriate to the prominent transitions. The emission processes are similar to those encountered in the solar corona and in laboratory plasmas, such as those inside tokamaks. Consequently, our ability to analyze spectra for these sources is reasonably well-developed. In contrast, for the second category, the X-ray photoionized nebulae, the physics is much more complex and many uncertainties remain. Although crude, "global" models of the ionization and thermal structure of the X-ray irradiated gas have been presented in the literature [2], very little attention has been devoted to detailed processes which may significantly affect the emerging spectra. Indeed, the few available data on X-ray binaries which have been collected with moderate resolution spectrometers already exhibit a number of discrete features which cannot be understood from simple considerations alone [3-4].

Since the astrophysical systems which involve X-ray photoionized nebulae are among the most exotic and interesting cosmic sources available for future observation, laboratory studies in the X-ray transfer physics relevant to their spectra are clearly warranted. We have discovered a novel approach to this research utilizing time-dependent measurements of laser plasmas. Laser plasmas share a number of similarities to cosmic X-ray photoionized nebulae: (1) First, they provide compact continuum X-ray sources which can be surrounded by lower density, ambient, preionized plasmas in a manner which closely resembles the geometry encountered in cosmic accretion-powered sources. (2) Second, in most laser plasmas, the recombination time scale greatly exceeds the time scale for plasma cooling via radiation or conduction. Thus, after the initial burst of energy deposition, the plasma is highly overionized relative to its temperature. This situation is also found in X-ray photoionized nebulae and is important in shaping the spectrum. (3) Finally, laser produced plasmas characterized by densities as high as 10^{20} cm^{-3} are known to be optically thick in the prominent resonance lines, even for low-Z elements. X-ray photoionized nebulae are also expected to be optically thick in most lines for parameters appropriate to many cosmic sources. Thus, line transfer effects are important in both cases.

A number of quite useful measurements can be performed with laser plasmas in this context. Here, we describe two initial experiments we are developing.

2. Measurement of photoabsorption cross-sections for partially stripped ions of abundant elements.

Absorption measurements in the soft X-ray and extreme ultraviolet bands are extremely important for cosmic accretion-powered sources as a probe of the cool, circumsource, accreting material [3]. Because the circumsource medium is photoionized, one expects a series of ionization fronts located sequentially outward from the central source [2]. Measurement of the individual ion column densities can thus yield sensitive constraints on physical conditions (density, temperature, geometry) in this ambient plasma. Of course, proper interpretation of the absorption spectra requires accurate knowledge of the short wavelength photoabsorption cross-sections. These have never been measured for most ions because of the general difficulties of producing large column densities of highly ionized material. Available values come almost exclusively from theoretical efforts, such as Hartree-Slater calculations, which are of varying accuracy [5]. The theoretical calculations generally do not include subtle effects, such as structure around autoionizing lines, which may be observable in the cosmic spectra.

Photoabsorption cross-sections can be measured by utilizing two laser plasmas, one to produce the background continuum radiation and one to serve as the target ionized plasma for the absorption experiment. A similar configuration has been invoked by Jannitti et al. [6] to measure absorption spectra of some light ions. It is essential in such an experiment that the background continuum dominate the continuum and line radiation from the target plasma. This can be accomplished by introducing a time delay between the two pulses. Since the recombination time scale is much larger than the cooling time scale, the target plasma will remain ionized after it has cooled. If the continuum-producing pulse occurs during this cool recombination-dominated phase, the target plasma can be observed cleanly in absorption.

Oxygen is probably the most important element for this kind of work. However, we have started with carbon since it is a solid at room temperature and is thus considerably easier to work with. We use thin carbon foils, ~ 1000 Å thick. When the laser pulse hits the foil, it burns through, advantageously minimizing density and temperature gradients at the center. Our experimental arrangement is illustrated in Figure 1. The target rod has a cylindrical section with a slit. This holds the foil as shown. Behind it is a thin, gold fiber. One beam from the laser is focussed to a line on the foil producing an elongated plasma. The other beam, time-delayed, is focussed through a hole in the rod onto the fiber where it produces a point plasma. X-ray light from the gold plasma passes through the carbon onto a concave, varied line-space reflection grating [7] where it is dispersed onto an imaging detector. Initially, we use a streak camera to provide time-resolved spectra necessary for fine-tuning the time delay between the two pulses. Later, we replace it with an X-ray framing camera which is electronically gated to the backlighter pulse. This yields a two-dimensional image, wavelength versus angle toward the backlighter. In the center, we are looking through the carbon plasma and see absorption. At the edges, we have an unobstructed view of the backlighter. Simple division yields the photoelectric attenuation as a function of wavelength.

As preparation for this experiment, we used a one-dimensional version of the LASNEX code at Livermore to calculate the hydrodynamics and radiation transport within the carbon plasma, and the XRASER code to find the detailed ionization structure. For a 3 J, 1 nsec, Nd:YAG pulse focussed to a 100 μm $\times$ 1 cm line, we find that the plasma remains mostly He-like at times exceeding 10 nsec after it is excited. In contrast, the electron temperature drops considerably after 5 nsec. Hence, the plasma becomes recombination-dominated as desired. Lower intensity pulses can be utilized to select out less ionized species.

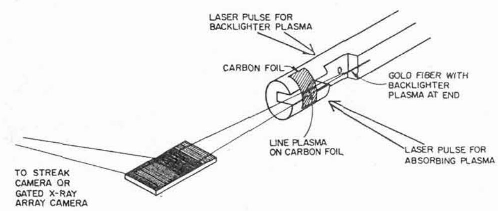

Figure 1: A schematic of the target configuration used for the carbon ion photoabsorption measurements. See text for description.

3. Optically-thick resonance line transfer.

As discussed earlier, for many cosmic sources of interest, the resonance lines of prominent ions are likely to be very optically-thick [2], so that line transfer is important. Of particular interest are line "leakage" channels associated with wavelength coincidences between resonance transitions of different ions. The multiplicity of ionization states which can coexist in close proximity in X-ray photoionized nebulae makes it likely that such processes can occur. Perhaps the best example is the well-known Bowen fluorescence mechanism in which He II Lα at λ303.782 pumps the nearly coincident O III $2p^2$ - 2p3d transitions at λ303.799 and λ303.693. The excited oxygen ion may then decay through the 2p3p and 2p3s levels to produce a number of optical "Bowen" lines along with additional extreme ultraviolet lines. One of these subsequent EUV transitions (O III λ374.436) is itself nearly coincident with the 2p - 3d resonance doublet of N III. Hence N III is also excited and can decay via the 3p and 3s channels to yield additional optical Bowen lines. This process was first identified in the 1930's [8], and a great deal of calculational work has since been devoted to it. It is now believed to occur in a large variety of diverse cosmic systems, including planetary nebulae, X-ray binaries, active galactic nuclei, and the solar transition region. However, it has never been demonstrated in the laboratory.

We are attempting to demonstrate the Bowen process using a premixed volume of helium, oxygen, and nitrogen which is photoionized into the appropriate states by a high temperature laser plasma in close proximity. The irradiated gas should cool and also enter a recombination-dominated state. When this occurs, the Bowen lines cannot be collisionally excited, so the dominant emission process should involve the Bowen mechanism. Kallman and McCray [9] show that the Bowen yield associated with this process should be very high at high optical depths for the He II Lα line. They calculate a critical optical depth at which the process saturates which is $\sim$ 80 $\times$ the He II/O III abundance ratio. The initial optical depths in our experiment should be very high, $\sim 10^4$ or so, well into the saturated regime. As the plasma expands, however, the optical depth decreases quadratically with radius. Thus by observing the time dependence of the Bowen yield, we can constrain the dependence on optical depth which is predicted by the calculations. The signal is weak, however, so a repetitive laser system is required for this work.

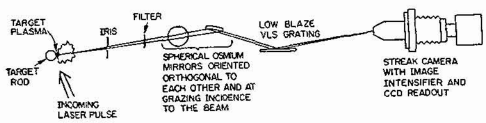

Figure 2: The spectrometer arrangement used for the laboratory demonstration of Bowen fluorescence. The "cloud" in front of the target represents the He-O-N gas mixture which is photoionized by X-rays from the laser plasma itself. See text.

A schematic of the laboratory set-up for this experiment is shown in Figure 2. In connection with this project we have developed a novel reflection grating spectrometer which incorporates a streak camera to provide the time-resolved measurements. It utilizes a flat varied line-space reflection grating which yields high resolution extreme ultraviolet spectra imaged on a focal plane at normal incidence to the beam [10]. Light from the plasma is focussed in both directions by a pair of spherical osmium mirrors oriented in a Kirkpatrick-Baez configuration. The converging light impinges on the grating where it is dispersed in the vertical direction. The streak camera is mounted at the focus of the mirrors with its slit aligned along the dispersion direction. We amplify the streak camera image with an image intensifier and read it out with a CCD camera. The system has been tested in the EUV and soft X-ray band. Near 304 Å, it delivers a resolving power of $\sim$ 500 - 1000 with a time resolution below 1 nsec. An example of its use is given in Figure 3 where we show a time resolved spectrum of an aluminum laser plasma in the soft X-ray band.

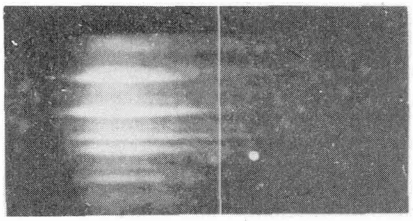

Figure 3: A time-resolved soft X-ray spectrum of an aluminum laser plasma obtained with the spectrometer arrangement depicted in Figure 2. Time increases to the right. The full width of the image represents $\sim$ 2 nsec. Wavelength increases toward the bottom. The two brightest lines at the top are resonance transitions of Li-like Al at 48.3 and 52.4 Å respectively. Notice how the spectrum evolves with time, i.e. different lines have markedly different temporal profiles.

4. Acknowledgements.

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