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New Measurements of Doubly Ionized Iron Group Spectra by High Resolution Fourier Transform and Grating Spectroscopy

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ABSTRACT

We report new measurements of doubly ionized iron group element spectra, important in the analysis of B-type (hot) stars whose spectra they dominate. These measurements include Co III and Cr III taken with the Imperial College VUV Fourier transform (FT) spectrometer and measurements of Co III taken with the normal incidence vacuum spectrograph at NIST, below 135 nm. We report new Fe III grating spectra measurements to complement our FT spectra. Work towards transition wavelengths, energy levels and branching ratios (which, combined with lifetimes, produce oscillator strengths) for these ions is underway.

1. Astrophysical Applications

Huge improvements in the quality of astrophysical spectra in recent years have not, in many cases, been matched by corresponding improvements in the laboratory measurements necessary to fully interpret them. Space-based spectrographs such as those onboard the

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Hubble Space Telescope (HST) — the Goddard High Resolution Spectrograph (GHRS) and its successor, the Space Telescope Imaging Spectrograph (STIS) — have pushed observations far into the vacuum UV (VUV) and, together with ground-based spectrographs such as HIRES at the Keck 1 telescope, are responsible for spectra of unprecedented resolution. Current laboratory measurements however are, in many cases, of too low an accuracy or lacking entirely in spectral regions required to interpret these astrophysical spectra accurately. Transition wavelengths with an uncertainty of a few parts in 10^7 and oscillator strengths accurate to within 10% are urgently needed by astronomers to interpret observations at high resolution.

Due to their relatively high abundance and line rich spectra, the Fe (3d) group elements dominate observed stellar opacity. Our measurements have included many neutral and singly ionized elements (for example, Cr I, Fe I, V I and II, Co I and II, Mn I and II and Ti II) in response to the above data needs. We have also undertaken a program of extensive measurements of doubly ionized Fe group elements, including Fe III, Co III and Cr III. The doubly ionized transition elements are important because they dominate the VUV region of hot (B-type) star spectra and the existing laboratory measurements are extremely poor.

2. Laboratory Measurements

A Fourier transform (FT) spectrometer (FTS) is based on a Michelson interferometer and offers the combination of a large free spectral range and high resolution. The unique high resolution Imperial College (IC) VUV FTS see (Pickering (2002)) uses a MgF_2 beam-splitter allowing measurements down to a world-record short wavelength of 135 nm in the VUV wavelength region. Transition wavelengths with an uncertainty of a few parts in 10^8 are achievable. The IC VUV FTS has a resolving power of 2,000,000 at 200 nm, corresponding to a resolution limit of 0.0001 nm. A hollow cathode lamp is used to excite neutral and singly ionized spectra, but this is unable to excite the doubly ionized species. For these, we use a Penning discharge lamp (PDL) (Heise *et al* (1994)) which provides the stable intensity output necessary for measurements by FTS.

With an FTS, the contribution to the noise in each line is distributed throughout the spectrum, thus producing a uniform noise level that can sometimes mask weaker lines. When this is the case, and also for measurements below the FTS wavelength cut-off (135 nm), we use the Normal Incidence Vacuum Spectrograph (NIVS) located at the National Institute of Standards and Technology (NIST), Maryland, USA. We recorded the NIVS spectra using phosphor image plates (see Reader *et al* (2000)) instead of photographic plates. These have the advantages over photographic media of greater availability, comparative sensitivity, and crucially, a linear intensity response that allows branching ratios to be calculated from measured intensities. Another advantage of the image plates is that they can be scanned

several times which allows stronger lines to be resolved, avoiding saturation effects observed with photographic plates.

3. Results

Co III & Cr III: 4p-4s Co III spectra, intensity calibrated with a D₂ lamp in the range 150 to 300 nm, have been recorded using the IC VUV FTS and the PDL. Image plate spectra have also been recorded for Co III in the range from about 250 nm down to below the ionization limit (approximately 37 nm). Analysis is underway. An example of a scanned image plate using the PDL with Co cathodes is shown in Fig. 1, and a spectrum extracted from one of the image plate tracks is shown in Fig. 2. Additional intensity calibrated, measurements of Co III spectra are planned to allow branching ratios, which can be combined with level lifetimes to yield oscillator strengths, to be calculated. Approximately 60 to 70 Cr III 4p-4s transition lines, several with a signal-to-noise ratio in the hundreds have also been recorded with the IC VUV FTS and the PDL. Again, analysis is underway.

Fe III: Fe III spectra have already been measured in the VUV with the IC VUV FTS (Pickering (2002)) covering several hundred 4p-4s transitions, the strongest of which have an uncertainty of 0.5 Å, an order of magnitude improvement in accuracy on previous measurements. These new measurements were supplemented by spectra measured in the infra-red (IR) by FT spectroscopy at NIST, and now by measurements recorded on image plates using the NIVS, which observed 4d-4p and 5s-4p transitions in the VUV that had been masked by noise from strong Fe II lines in the FT spectroscopy measurements at Imperial College.

Analysis planned and underway includes producing intensity and wavelength / wavenumber calibrated linelists and completing term analysis, i.e. classifying the transition lines and establishing the energy level structure by firstly using known energy levels to classify as many lines as possible, and then using the unidentified lines, combined with the known energy levels, to calculate possible new energy levels that can be verified by theoretical predictions.

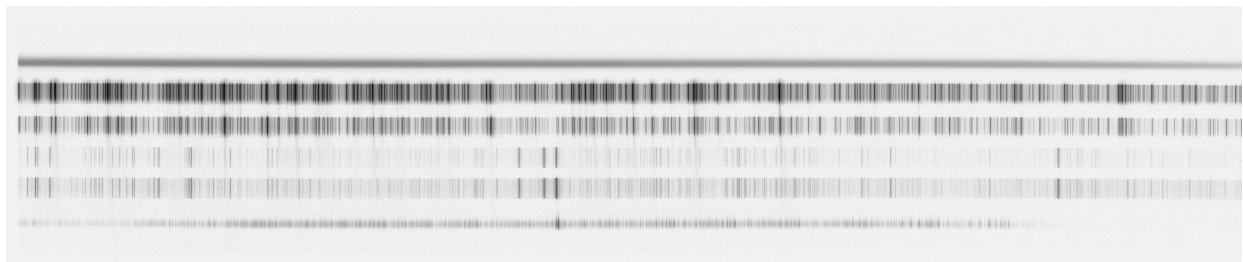


Fig. 1.— A NIVS image plate scan. The top & bottom images are for a D₂ lamp, and the others are for Co in the PDL for different angles of incidence and running conditions.

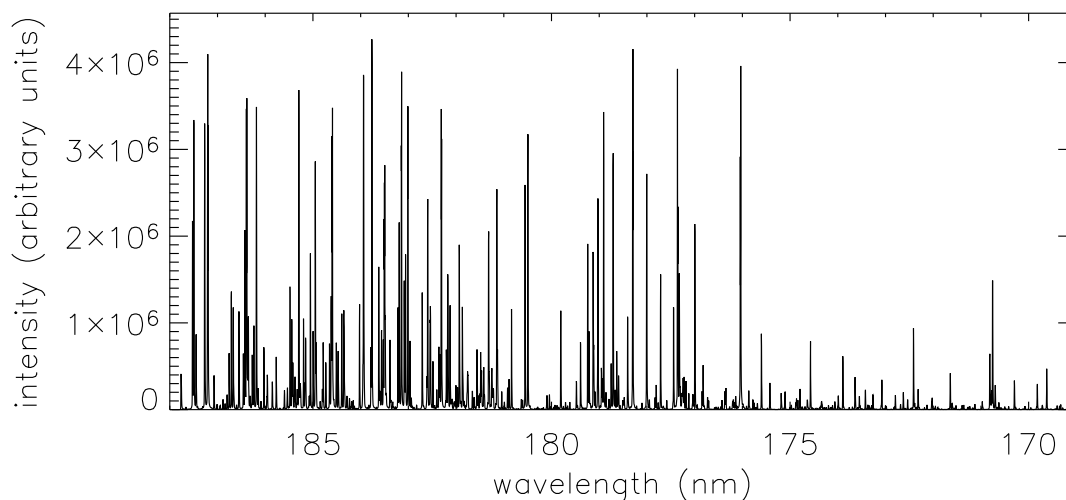


Fig. 2.— A spectrum of Co cathodes in the PDL, extracted from the image plate scan shown in Fig. 1 (second track from the top).

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REFERENCES

- Pickering, J. C. 2002, *Vib. Spec.*, 29, 27
Heise, C., Hollandt, J., Kling, R., Kock, M., & Kühne, M. 1994, *Appl. Optics*, 33, 5111
Reader, J., Sansonetti, C. J., & Deslattes, R. D. 2000, *Appl. Optics*, 39, 637