Ultraviolet imaging of exoplanets

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1 Disclaimer

Direct exoplanet observations are nominally the province of the EXOPAG and are thus beyond the scope of this RFI. However, the authors feel that given the synergy between exoplanet observations in general, and direct ultraviolet imaging of exoplanets in particular, and ultraviolet astrophysics that this response is warranted.

2 Move to characterizing exoplanets

The study of extrasolar planets is one of the most exciting endeavors of modern science. The statistics are familiar and impressive. To date over 750 planets have discovered in about 600 planetary systems — and that is not counting the thousands of Kepler planet candidates awaiting confirmation.

The advent of high quality ultraviolet transiting observations (e.g. Vidal-Madjar et al., 2003, 2004; Linsky et al., 2010; Schlawin et al., 2010; Fossati et al., 2010; Sing et al., 2011) and possibly more, better, ultraviolet observations in the future (see France et al. response to this RFI) go a long way to furthering our understanding of the diverse properties of exoplanetary atmospheres. They have given us information about the composition, ionization, and dynamics (including the rates of atmospheric escape) of the atmospheres of a few planets.

Indeed, it is not at all surprising that ultraviolet spectroscopy has given us a large information return from the relative few observation which have been possible so far. Ultraviolet spectroscopy is central to our studies of planets in the solar system. It is a central tool in our studies of aurora on the Earth (Meier, 1991) and other planets (Feldman et al., 1993) and it reveals the similarities and differences of the interaction of the sun (both as an ultraviolet light source and as a particle source) with the upper atmospheres of the solar system planets (Clarke et al., 2005). Furthermore, since the emissions of solar system planets arise from electron impact and fluorescent sources, the emissions are not bounded by the star's

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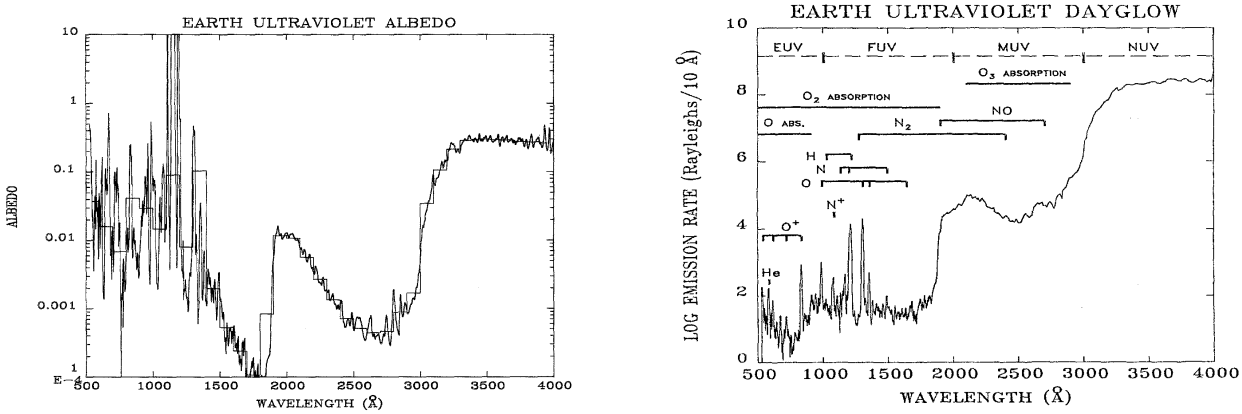

Figure 1: The spectrum and "albedo" of the Earth in the far ultraviolet is no lower than in the visible and, in select atomic and molecular transitions, can be higher than 1. This is because the far ultraviolet emissions arise from fluorescence and electron impact rather than thermal or scattering processes as they do in the infrared and visible. As a result the planet can emit more light than it receives from its host star at some wavelengths. Figures from Meier (1991).

intensity at the wavelength being observed - fluorescence will redistribute light from bright stellar lines to dimmer spectral regions and electron impact lines will appear in relatively faint stellar bands.

3 The need for imaging

Simple geometry heavily biases the systems which can be studied by transit methods to planets in close orbits. The search volume needed to find a transiting exoearth around a sunlike star at 1 AU will likely result in detections which are unsuitable to detailed follow up observations. The systems which are suited to transit spectroscopy are the extremophiles of planetary atmospheres; they will not tell us much about Earthlike or solar system like planets. In order to study planetary systems like the solar system in age, orbital configuration, and stellar type we are going to need to directly image systems which are not transiting.

This will have a profound impact on exoplanet science and our understanding of our place in the Galaxy. Astro2010 sees "Identification and characterization of nearby habitable exoplanets" as one of the "Science frontier discovery areas." This need, which is gradually being met, has been apparent from the earliest days of exoplanet observations. Soon after the first extrasolar planet was discovered, a group of scientists and engineers prepared a roadmap for the Exploration of Neighboring Planetary Systems (ExNPS). In their report they noted that *"Direct detection methods have to be sensitive enough to make high signal-to-noise detections of planets in just a few hours so that a large number of sources can be surveyed to a meaningful level, and so that crude spectroscopy can be carried out with the same apparatus to provide an initial characterization of the detected planets."* They further

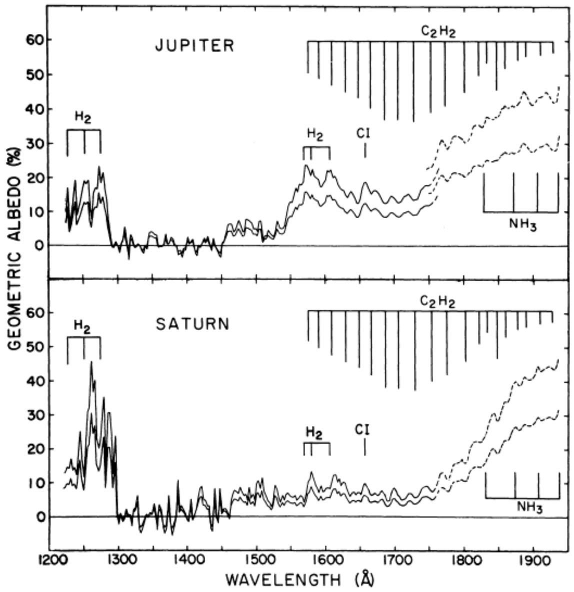

Figure 2: The "albedo" of the Jupiter and Saturn in the far ultraviolet. Like Earth, the "albedo" of the Earth in the far ultraviolet is no lower than in the visible and, in select atomic and molecular transitions at high resolution, can be higher than 1. Figure from Clarke et al. (1982).

stated "The goal of imaging a terrestrial planet is taken to mean making an image – a family portrait or an orrery – of the planet(s) in a planetary system around a nearby star and identifying whether any of these planets are habitable".

4 The need for ultraviolet imaging

Technology has advanced to the point where the first visible and near infrared images of such planetary system are being recorded (e.g. Kalas et al., 2008; Marois et al., 2008). Those first images are giving us information about the albedos and energy balance of extrasolar planets. However, much more will be learned from ultraviolet spectroscopy. The clouds on earth or the band structure of Jupiter can be seen in the visible and can tell us a lot about those objects but much more can be learned from the ultraviolet spectra of those bodies. The ultraviolet region contains the resonance lines of HI, OI, H_2, N_2, O_2, O_3, and many other important species (see figure 1). Ultraviolet coronagraphy would allow us to probe all of them.

5 Why ultraviolet imaging is possible

As usual with exoplanet research, the desirability of a particular observation is much more obvious than the achievability of that observation. In order to carry out UV exoplanet imaging one will need an ultraviolet coronagraph of combined with a spectrometer capable of recording spectra with enough resolution to "peak up" the ultraviolet emission lines under consideration. The spectrograph will also allow spectral differential imaging to improve the performance of the coronagraph. Such an instrument is beyond our current capability but the technologies which need to be improved are not fully mature so there is reason to believe that progress can be made.

5.1 Smaller telescopes

While it is clear that moving to the ultraviolet spectral region poses challenges beyond those already present with visible or near infrared coronagraphy it also brings some benefits. The canonical exoplanet mission (Levine et al., 2009) envisions a 4 meter class telescope with a coronagraph operating at 4 λ/d . By moving to the ultraviolet we will see an advantage of at least 3 and as much as 10 in this critical metric. This means that, with the same telescope and target, observations will be at 12 to 40 λ/d . On the other hand, the same diffraction limit could, in principle, be achieved with a telescope in the 0.5 to 1.5 meter range.

5.2 Tighter tolerances

To achieve this performance one will need to improve the optical figure of the coronagraphs and optical systems by a similar factor (3 to 10). While this is by no means trivial, there is reason to think that it is possible. Recent advances in adaptive optics have shown that wavefront control is possible at the 0.1 nm level on small scales (Trauger et al., 2011), and there seems to be no reason that is cannot be achieved at larger scales. Between the improved optical quality of EUV optics and rapidly improving adaptive optics the required optical performance should be achievable.

5.3 Fainter targets

In addition to the tighter tolerances UV observations of late stars will result in much fainter targets. The spectrum of the sun is approximately 10^6 times fainter in the ultraviolet than in the visible. With a 2.4 meter class telescope is will take an observation of approximately 5 days to observe a planet around even a fairly bright G star. It should be noted that this estimate may be somewhat pessimistic. France et al. (2010b) observed HD209458 and identified an emission feature at the orbital velocity of the planet *without a coronagraph*. France et al. (2010a) observations of J12073346-3932539 likewise may be detecting emission from that planet. The physics and planetary conditions of these observations are far from clear but they do give some indication that the observations may be easier than we are assuming here.

6 Science returned

The science return from such a program is considerable. In figure 3 we show that far ultraviolet imaging can distinguish between strong and weak magnetic fields. In figure 1 we present the ultraviolet spectrum of Earth, which shows strong absorption in the O_2 and

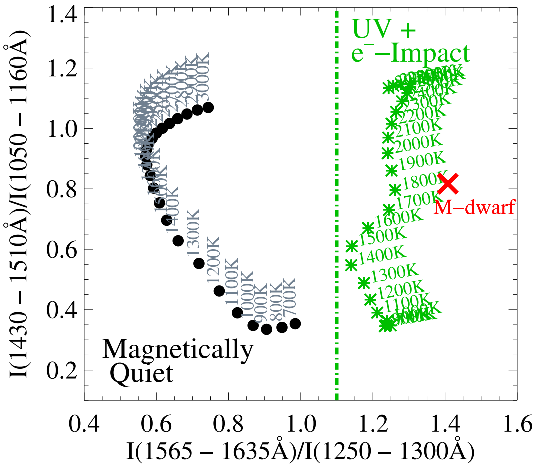

Figure 3: Far-ultraviolet "color-color" plots for gas giant planets with a range of surface temperatures. The plots are based on models of H_2 emission spectra in four narrow bands from 1050 - 1635 Å. These objects are readily separated by the presence/absence of electron-impact emission, which should depend strongly on the presence of a planetary magnetic field. Therefore, narrow-band far-UV imaging of exoplanets can provide constraints on the prevalence of planetary magnetic fields in extrasolar systems.

O_3 bands which are thought to be evidence of life. These are just two examples of the power of ultraviolet imaging of exoplanets.

7 What we need

In order to achieve these observations several technology improvements are required. We need wavefront control at the 0.1 nm level. We need high quantum efficiency ultraviolet detectors with very low dark noise. We *do not* need particularly large apertures.

While the technology improvements needed are significant, such a mission is achievable.

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