Planetary and Space Science 103 (2014) 291–298

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Isolating auroral FUV emission lines using compact, broadband instrumentation

P.M. Molyneux[a,*], N.P. Bannister[a], E.J. Bunce[a], D. Grodent[b], J.T. Clarke[c], K. Fleury-Frenette[d], J.-C. Gérard[b], J. Lapington[a], J.D. Nichols[a], E. Renotte[d], L. Rossi[d]

[a] Department of Physics and Astronomy, University of Leicester, University Road, Leicester, UK
[b] LPAP, Institut d'Astrophysique et de Géophysique, Université de Liège, Liège, Belgium
[c] Center for Space Physics, Boston University, 957 Commonwealth Ave., Boston, MA 02215, USA
[d] Centre Spatial de Liège, Université de Liège, Liège, Belgium

ARTICLE INFO

Article history:
Received 25 April 2014
Received in revised form
17 July 2014
Accepted 7 August 2014
Available online 20 August 2014

Keywords:
FUV imaging
FUV spectroscopy
Ganymede
Aurora
Atmospheres

ABSTRACT

Images of auroral emissions at far ultraviolet (FUV, 122–200 nm) wavelengths are useful tools with which to study magnetospheric–ionospheric coupling, as the scattered sunlight background in this region is low, allowing both dayside and nightside auroras to be imaged simultaneously. The ratio of intensities between certain FUV emission lines or regions can be used to characterise the precipitating particles responsible for auroral emissions, and hence is a useful diagnostic of magnetospheric dynamics. Here, we describe how the addition of simple transmission filters to a compact broadband imager design allows far ultraviolet emission ratios to be deduced while also providing large-scale instantaneous images of the aurora. The low mass and volume of such an instrument would make it well-suited for both small satellite Earth-orbiting missions and larger outer planet missions from which it could be used to characterise the tenuous atmospheres observed at several moons, as well as studying the auroral emissions of the gas giants. We present a study to investigate the accuracy of a technique to allow emission line ratio retrieval, as applied to the OI 130.4 nm and 135.6 nm emissions at Ganymede. The ratio of these emissions provides information about the atmospheric composition, specifically the relative abundances of O and O_2. Using modelled FUV spectra representative of Ganymede's atmosphere, based on observations by the Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS), we find that the accuracy of the retrieved ratios is a function of the magnitude of the ratio, with the best measurements corresponding to a ratio of ~ 1.3.

1. Introduction

The far ultraviolet (FUV) spectral region is commonly used for auroral imaging, since several important atmospheric species, including atomic oxygen and molecular nitrogen, produce prominent FUV emissions, and the low solar flux and atmospheric reflectivity in this band result in a greatly reduced scattered sunlight background compared to that at visible wavelengths. At Earth, the brightest useful FUV auroral emissions are two oxygen multiplets – the optically allowed OI ($^3S^\circ$–^3P) triplet at 130.4 nm and the semi-forbidden OI ($^5S^\circ$–^3P) doublet at 135.6 nm – and the Lyman–Birge–Hopfield (LBH) bands of N_2, which are often considered to consist of two spectral regions: LBH-short (140–160 nm) and LBH-long (160–180 nm). Since each of these emissions is caused by electron impact excitation, isolation of the emissions allows characterisation of the flux and energy spectrum of the responsible precipitating electrons, which are useful diagnostics of magnetospheric dynamics. For example, LBH-short emissions are absorbed by the Schumann–Runge continuum of O_2, while LBH-long emissions are not. As the concentration of atmospheric O_2 is a function of altitude, the ratio of LBH-short to LBH-long intensity allows the determination of the depth of penetration, and hence energy, of the impinging electrons (e.g. Germany et al., 1990).

Here, we describe work to show that useful spectral information may be extracted from auroral images obtained by a compact broadband FUV imager by the introduction of two simple, commercially available transmission filters to the optical design. The study described was performed during the development of an imager proposed for ESA's JUpiter ICy moons Explorer (JUICE) mission to Jupiter, but the instrument design is also suited to

---

* Corresponding author. Tel.: +44 116 252 5850.
E-mail address: pmm13@leicester.ac.uk (P.M. Molyneux).

http://dx.doi.org/10.1016/j.pss.2014.08.007
0032-0633/© 2014 Elsevier Ltd. All rights reserved.

observations of other FUV-emitting objects, including the Earth, and its low mass and volume should make it particularly attractive for small satellite missions.

Previous attempts at spectral isolation by auroral imagers have made use of various methods, with mixed results. The Viking and Freja satellites each carried two compact Cassegrain cameras with different broadband filters covering 134–180 nm and 123.5–160 nm (125–160 nm for Freja) to allow some wavelength selection (Anger et al., 1987; Murphree et al., 1994). The throughput of one camera was thus dominated by LBH-long emissions, while the other was mainly sensitive to the 130.4 nm atomic oxygen line. This limited the accuracy of any electron information derived from the ratio of emission intensities measured by the two cameras, since the relative intensities of the N_2 and O emissions are affected by the N_2/O ratio in the atmosphere, which is not constant but varies with altitude and magnetospheric activity (e.g. Mayr and Volland, 1972; Hays et al., 1973). Better wavelength selection was achieved by the Polar UVI instrument using multilayer filters, which consist of alternating layers of high- and low-refractive index materials with carefully selected optical thicknesses such that light reflected from the boundaries between the layers experiences constructive interference at the wavelength of interest and destructive interference at other wavelengths. The Polar UVI oxygen filters each had 5 nm wide bandpasses and average out-of-waveband blocking of better than $3\times10^{-3}\%$ (Zukic et al., 1993), but the filters required a 45° angle of incidence, increasing instrument complexity – the Polar UVI mass of 21 kg was substantially larger than the 7 kg (9.1 kg) total mass for the Viking (Freja) cameras (Torr et al., 1995; Anger et al., 1987; Murphree et al., 1994). Good FUV wavelength discrimination may also be achieved with the use of imaging spectrometers, such as the Spectrographic Imager (SI) on IMAGE (Mende et al., 2000; IMAGE also carried a Wideband Imaging Camera (WIC) based on the Viking/Freja Cassegrain design) but, as with the Polar UVI filters, this comes at the cost of increased instrument complexity and reduced throughput. Typically, an imaging spectrograph will have a narrow field of view and must therefore build up auroral images by scanning over the auroral region, and so is unable to provide an instantaneous view of auroral morphology in the same way that a conventional imager can. Such large-scale, instantaneous images are vital for an understanding of short-timescale magnetospheric dynamics.

To clarify the purpose and advantage of our proposed filter design, we summarise the key elements of the instrument for which it was originally designed, before considering its applications to other mission opportunities.

2. Basic instrument overview

The Jupiter system Ultraviolet Dynamics Experiment (JUDE) was a wide-field UV imager proposed for the JUICE mission by an international consortium led by the Université de Liège and the University of Leicester. A schematic showing the JUDE optical layout is given in Fig. 1. The instrument was designed to accommodate a large dynamic range, responding to both the most intense (~mega Rayleigh Gérard et al., 1994; Ballester et al., 1996; Prangé et al., 1998; Waite Jr et al., 2001) emissions from Jupiter's FUV aurora and the weak (~10 s of Rayleigh Hall et al., 1995, 1998; Roesler et al., 1999; Feldman et al., 2000; Strobel et al., 2002) emissions from the atmospheres of the Galilean moons. A 6° instrument field of view would allow the full disc of Jupiter to be imaged from a distance of $\sim 9.5R_J$ – the closest approach made by JUICE in the Jupiter orbit phases of the mission. Full-disc imaging of Ganymede, Callisto and Europa would also have been possible during flybys of the moons. The spatial resolution of the imager was designed such that when viewing Jupiter's aurora from Ganymede orbit, the resolution would have improved on the best Hubble Space Telescope (HST) images of the Jovian aurora. STIS FUV images have an angular resolution limited by the FUV-MAMA detector, which has a point spread function of $\sim 0.1''$ at 143 nm (Walsh, 1997). At the closest possible Earth–Jupiter distance of ~3.95 AU, the best spatial resolution achievable by the STIS FUV-MAMA is therefore ~286 km. JUDE's angular resolution of 20 arcsec corresponds to a spatial resolution of ~100 km when observing Jupiter's aurora from orbit around Ganymede, a distance of $\sim 15R_J$ from Jupiter. In addition to this improved spatial resolution, the use of an imager rather than a scanning instrument would have provided an inherently high temporal resolution. The combination of the wide field of view, large dynamic range and high spatial and temporal resolution would allow the FUV emissions from Jupiter and its moons to be more comprehensively studied than previously possible, with unprecedented resolution and coverage. When combined with in situ particle and magnetic field data from other JUICE instruments, the JUDE auroral images would have provided new insights into the dynamic processes within Jupiter's magnetosphere and the magnetosphere–ionosphere coupling there.

Although JUDE was not selected for JUICE, its compact, simple normal incidence design makes it an attractive option for other planetary missions or small Earth-observation satellites, particularly if some spectral capabilities can be added without a corresponding increase in the instrument complexity. The possibility of adding a spectral discrimination method was investigated for JUDE, with the aim of increasing the instrument science yield by allowing some characterisation of the atmospheres of the Galilean moons.

JUDE's optics consist of nickel-plated aluminium mirrors, onto which multilayer reflective coatings are deposited. The instrument bandpass is 122–165 nm, with the mirror coatings designed to maximise the throughput around 130–143 nm (the mirror response is shown in Fig. 2). Placing two or more normal-incidence

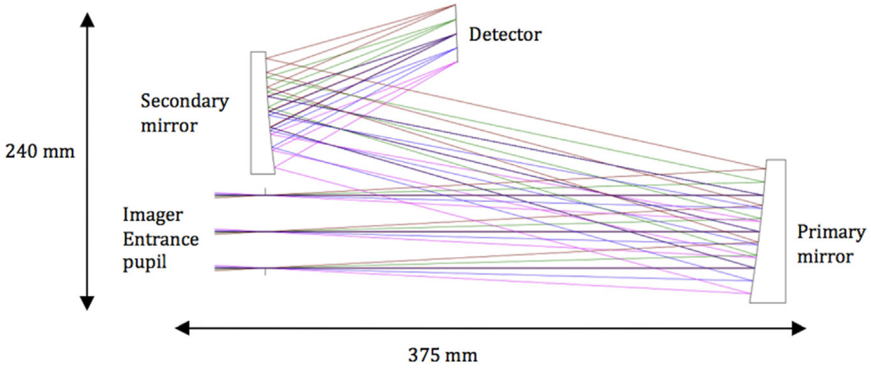

Fig. 1. Schematic showing the basic optical layout proposed for the JUDE imager.