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Saturn's aurora observed by the Cassini camera at visible wavelengths

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ABSTRACT

The first observations of Saturn's visible-wavelength aurora were made by the Cassini camera. The aurora was observed between 2006 and 2013 in the northern and southern hemispheres. The color of the aurora changes from pink at a few hundred km above the horizon to purple at 1000–1500 km above the horizon. The spectrum observed in 9 filters spanning wavelengths from 250 nm to 1000 nm has a prominent H-alpha line and roughly agrees with laboratory simulated auroras. Auroras in both hemispheres vary dramatically with longitude. Auroras form bright arcs between 70° and 80° latitude north and between 65° and 80° latitude south, which sometimes spiral around the pole, and sometimes form double arcs. A large 10,000-km-scale longitudinal brightness structure persists for more than 100 h. This structure rotates approximately together with Saturn. On top of the large steady structure, the auroras brighten suddenly on the timescales of a few minutes. These brightenings repeat with a period of $\sim$1 h. Smaller, 1000-km-scale structures may move faster or lag behind Saturn's rotation on timescales of tens of minutes. The persistence of nearly-corotating large bright longitudinal structure in the auroral oval seen in two movies spanning 8 and 11 rotations gives an estimate on the period of 10.65 ± 0.15 h for 2009 in the northern oval and 10.8 ± 0.1 h for 2012 in the southern oval. The 2009 north aurora period is close to the north branch of Saturn Kilometric Radiation (SKR) detected at that time.

1. Introduction

Before Cassini arrived at Saturn, saturnian aurora was observed in both UV and infrared (IR) wavelengths, as reviewed by Kurth et al. (2009). Substantial auroral research at Saturn has been undertaken since then. This includes Cassini UV and IR movies (Pryor et al., 2011; Carbary, 2012; Badman et al., 2011), radio data (Provan et al., 2013; Cowley and Provan, 2013), and magnetospheric particle maps (Lamy et al., 2013). Also Earth-based observations of UV aurora and solar wind were performed (Clarke et al., 2009; Grodent et al., 2010). Good summaries of the recent discoveries are given by Lamy et al. (2013) and Grodent (2014).

Particles precipitating to the upper atmosphere of Saturn form circumpolar auroral ovals, as on Earth and Jupiter, however the origin of these particles is controversial. Correlation of auroral dynamics with the solar wind suggests that the aurora is at least partly driven by solar wind, possibly with the boundary between open and closed magnetic field lines projecting to the main auroral oval, as on Earth. However, solar-wind-independent variability of aurora suggests that the aurora is also driven by internal disturbances of the ion-loaded magnetosphere (e.g., modeled by Cowley et al., 2004; Goldreich and Farmer, 2007; Gurnett et al., 2007), as on Jupiter. This mass loading is produced by volcanic activity on Jupiter's and Saturn's moons. UV and infrared aurora and SKR show some correlation with solar wind (GéRard et al., 2005; Stallard et al., 2012; Nichols et al., 2014), however the aurora also varies independently (Clarke et al., 2009). This leaves the question of the origin of Saturn's aurora open for observers and modelers.

This paper is the first to report detection of aurora in visible light by the Cassini camera in 2006. Visible-light images and movies by the Cassini camera show aurora at unprecedented spatial resolution as fine as tens of km per pixel, and also at unprecedented time resolution as fine as one minute. Previous detections of auroral ovals and 500-km-scale arcs and spots in UV had spatial resolution of hundreds of km (GéRard et al., 2004; Stallard et al., 2008; Grodent et al., 2011; Radioti et al., 2014). Visible aurora is harder to detect than UV and IR aurora because in visible wavelengths daylight interferes with the auroral light. The auroral brightness is only 10^{-6}–10^{-5} (10^{-4}–10^{-3} per cent) of the brightness of sunlit dayside of Saturn. Because of that, visible aurora can only be observed on the night side. Only spacecraft near Saturn can observe the night side and detect visible aurora. Similar restrictions apply to Jupiter, where visible aurora was first observed in Galileo spacecraft images (Vasavada et al., 1999).

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Here we present all the visible auroral observations starting with Cassini's arrival at Saturn in 2004 until March 2014. Section 2 describes Saturn's aurora morphology and location. Section 3 reveals the timescales of auroral variations. Section 4 reports the spectrum of the auroras obtained with different filters on the camera, together with the vertical structure of aurora. Details of image processing and a list of all auroral detections are presented in the Appendix.

2. Auroral morphology and location

Fig. 1 shows the discovery images of Saturn's visible aurora taken on July 16, 2006. The Cassini camera is observing the north polar area at night. In the raw images (Panels 1 and 3), Saturn's limb is a dark silhouette against the brighter background of the "clear sky". The "clear sky" shows star trails and some opacity source behind the planet, possibly E-ring material, which will be the subject of a separate research. The raw images (Panels 1 and 3) are processed for noise reduction and shown again in Panels 2 and 4, respectively.

2.1. Image processing

To enhance the contrast of the faint aurora on the noisy background we used two techniques. First, we took advantage of the variable nature of the aurora during the multiple-frame movies. For each movie, we constructed the average image from all movie frames not containing obvious aurora, i.e., the background image. Then we subtracted that background image from each frame in the movie. This left only the variable part of the brightness, which is predominantly aurora. This technique removes stray light in the camera, detector defects such as vertical stripes of uneven sensitivity, and rings produced by dust particles in the camera (see the raw images in Fig. 1 panels 1 and 3). It also would remove the non-variable part of the aurora, which we are therefore not able to detect. This includes permanent auroral structures fixed in local time. Without background subtraction non-variable aurora usually also cannot be detected because it is indistinguishable from the stray light. Sometimes images containing aurora had to be used for the background subtraction. This resulted in oversubtraction and produced permanent dark spots in the resulting movies.

The second noise-reduction technique was the removal of bad detector pixels and cosmic ray hits. We did this by automatic selection of single pixels that are significantly brighter than any neighboring pixels and replacing them with the average brightness of the neighboring pixels. This enhances the aurora because the aurora is diffuse and rarely has one-pixel structures in it. Such removal of bad pixels is important while estimating average auroral brightness, to which they could contribute substantially.

On the day shown in Fig. 1, five night-side images were obtained, two of which show auroras. They were observed from nearly the same point in space, while Saturn rotated in front of the spacecraft to reveal different longitudes. The three images not containing aurora were averaged as a "background image", which was then subtracted from the images in Fig. 1. As will be discussed later, after filtering out the local time effects, nearly-corotating auroral structures are seen in the visible movies, which makes it useful to map the aurora in standard System III longitude. System III coordinates assume planetocentric latitude and

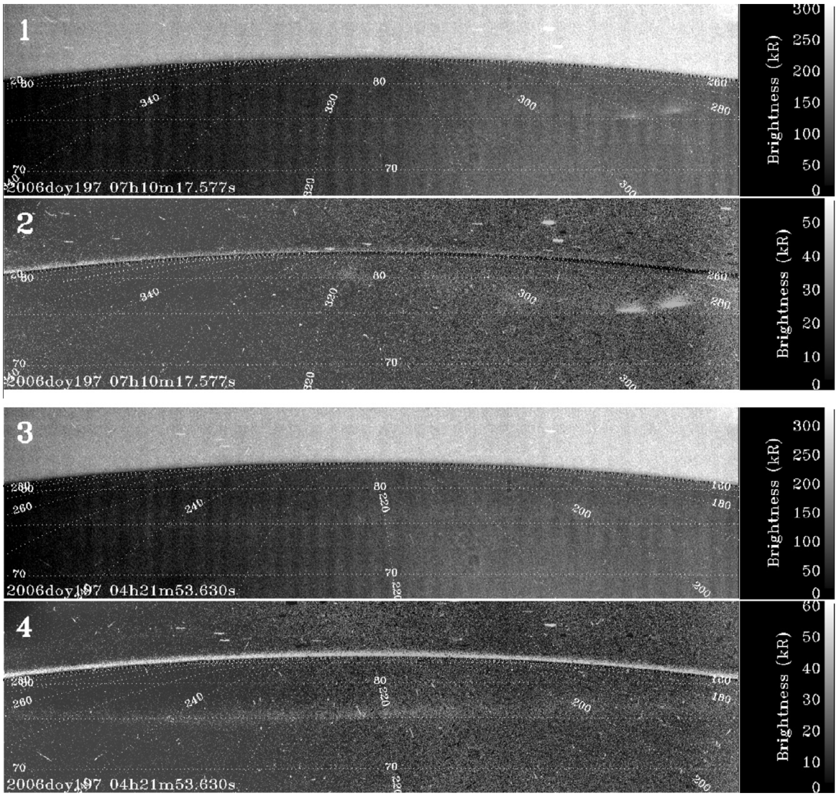

Fig. 1. Images of Saturn aurora on July 16 (which is Day of Year, or DOY 197), 2006. Panels 1 and 3 show original images converted to brightness units of Rayleighs ($1R = 10^{10} (photons) m^{-2}\ s^{-1}$, see the kilo-Rayleigh (kR) scale bar on the right). A constant brightness value was subtracted from each image to account for stray light in the camera. The value was chosen to maximize the image contrast. Panels 2 and 4 show the same images with the average of three other similar images (i.e. "background image") subtracted to reveal aurora changing from image to image. A west longitude and planetocentric System III latitude grid overlays the images. The date and time are labeled in the lower left of each panel. Each image was taken using a broadband filter spanning the entire range of visible wavelengths 250 to 1000 nm, which is the CL1 + CL2 filter combination (see filter details in Porco et al., 2004). The filter shape is shown in Fig. 8.