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New constraints on Ganymede's hydrogen corona: Analysis of Lyman-α emissions observed by HST/STIS between 1998 and 2014

Juan Alday [a,*], Lorenz Roth [a], Nickolay Ivchenko [a], Kurt D. Retherford [b,d], Tracy M. Becker [b], Philippa Molyneux [b], Joachim Saur [c]

[a] *School of Electrical Engineering, Royal Institute of Technology KTH, Stockholm, Sweden*
[b] *Southwest Research Institute, San Antonio, TX, USA*
[c] *Institute of Geophysics and Meteorology, University of Cologne, Cologne, Germany*
[d] *University of Texas at San Antonio, San Antonio, TX, USA*

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A B S T R A C T

Far-ultraviolet observations of Ganymede's atmospheric emissions were obtained with the Space Telescope Imaging Spectrograph (STIS) onboard of the Hubble Space Telescope (HST) on several occasions between 1998 and 2014. We analyze the Lyman-α emission from four HST campaigns in order to constrain the abundance and variation of atomic hydrogen in Ganymede's atmosphere. We apply a forward model that estimates surface reflection and resonant scattering in an escaping corona of the solar Lyman-α flux, taking into account the effects of the hydrogen in the interplanetary medium. The atmospheric emissions around Ganymede's disk derived for the observations taken between 1998 and 2011 are consistent with a hydrogen corona in the density range of (5–8) $\times$ 10^3 cm^{-3} at the surface. The hydrogen density appears to be generally stable in that period. In 2014, Ganymede's corona brightness is approximately 3 times lower during two observations of Ganymede's trailing hemisphere and hardly detectable at all during two observations of the leading hemisphere. We also investigate extinction of Ganymede's coronal emissions in the Earth's upper atmosphere or geocorona. For small Doppler shifts, resonant scattering in the geocorona of the moon corona emissions can effectively reduce the brightness observed by HST. In the case of the 2014 leading hemisphere observations, an estimated extinction of 80% might explain the non-detection of Ganymede's hydrogen corona. Geocoronal extinction might also explain a previously detected hemispheric difference from Callisto's hydrogen corona.

1. Introduction

Ganymede is the largest moon in our Solar System ($R_G = 2634$ km), and it is the only known moon to possess its own intrinsic magnetic field (Kivelson et al., 1996). Measurements made by the Galileo spacecraft near Ganymede revealed that its interior has differentiated into a metallic core of radius 400–1300 km, which is surrounded by a silicate mantle, and enclosed by an ice shell (Anderson et al., 1996). Using data from the Galileo magnetometer, Kivelson et al. (2002) proposed the existence of a subsurface ocean, at a depth of approximately 150 km, sandwiched between two ice layers. In order to verify the existence of the subsurface ocean, Saur et al. (2015) analyzed the response of Ganymede's auroral ovals to Jupiter's time-periodic magnetic field using observations made with the Hubble Space Telescope (HST). They conclude that the observations require the presence of a subsurface saline ocean.

Ganymede's surface is divided into two major terrain types: bright younger regions covering approximately 65% of the surface, and ancient dark terrain covering the remaining 35% (Shoemaker et al., 1982). The bright areas are known to be rich in water ice, while the dark regions contain a larger fraction of rocky material (Carlson et al., 1996). Spatially resolved images from the Galileo spacecraft suggest that the water-ice is particularly concentrated in the polar regions and the visibly brighter leading hemisphere (Hansen and McCord, 2004). On the other hand, the trailing hemisphere is darker, presumably indicating more non-ice contaminant there.

The detection of Ganymede's atmosphere was first reported by Carlson et al. (1973) from a stellar occultation measurement, but this was later rejected by an upper limit measurement by Voyager UVS (Broadfoot

* Corresponding author.
E-mail addresses: juanap@kth.se (J. Alday), lorenzr@kth.se (L. Roth), nickolay@kth.se (N. Ivchenko), k.retherford@swri.edu (K.D. Retherford), tracy.becker@swri.edu (T.M. Becker), philippa.molyneux@swri.edu (P. Molyneux), saur@geo.uni-koeln.de (J. Saur).

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et al., 1981). The atmosphere is generated by sublimation and sputtering of the surface (Yung and McElroy, 1977; Brown et al., 1978; Lanzerotti et al., 1978). As water ice is the main constituent of the surface, the atmosphere is expected to possess elements from the water species (H_2O, H_2, O_2, OH, O, H). Indeed, the presence of O_2 (Hall et al., 1998) and H (Barth et al., 1997) in Ganymede's atmosphere has been confirmed.

Hall et al. (1998) reported the first detection of auroral emission from Ganymede, with observations made with the Goddard High Resolution Spectrograph (GHRS) on the HST. From these observations, an O_2 column density in the range of (1–10) × 10^{14} cm^{-2} was derived based on the brightness of the OI 1356 Å and OI 1304 Å oxygen lines. Subsequently, images of Ganymede's FUV aurora were obtained with the Space Telescope Imaging Spectrograph (STIS) on HST, both of the trailing and leading hemispheres (Feldman et al., 2000; Eviatar et al., 2001; McGrath et al., 2013; Saur et al., 2015; Musacchio et al., 2017). The observations suggest that Ganymede possesses two auroral ovals, which are located near the open-closed field line boundary (OCFB) (McGrath et al., 2013). The location of the ovals presents a hemispherical difference, being at higher latitudes on the trailing hemisphere compared to the leading side (McGrath et al., 2013). Eviatar et al. (2001) also proposed that the plasma electrons must be locally accelerated within Ganymede's magnetosphere in order to produce the observed intensities.

Atomic hydrogen in Ganymede's atmosphere was first detected by the ultraviolet spectrometer on the Galileo spacecraft (Barth et al., 1997). The observed Lyman-α brightness suggested the presence of a hydrogen corona with a tangential column density of 9.2 × 10^{12} cm^{-2}. Feldman et al. (2000) analyzed the Lyman-α emission near Ganymede in HST/STIS images taken on 1998 October 30, and reported that the observed brightness was consistent with the results from Barth et al. (1997). The analysis of the Lyman-α emission on HST/STIS images has been also used to detect the presence of atomic hydrogen on Europa (Roth et al., 2017b) and Callisto (Roth et al., 2017a). Their results revealed a hydrogen corona with a surface density in a range of (1.5–2.2) × 10^3 cm^{-3} on Europa and (2.6–4.9) × 10^3 cm^{-3} on Callisto.

Several efforts have been made in order to model the dynamics and structure of Ganymede's atmosphere, mostly focusing on the H_2O and O_2 distribution, as they are expected to be the most abundant constituents in the atmosphere (Marconi, 2007; Turc et al., 2014; Leblanc et al., 2017; Plainaki et al., 2015), although the results could be over-estimated, since the effect of surface impurities on the sublimation rates of water ice (Spencer, 1987) are often not considered in the models. In general, the models predict an atmosphere dominated by H_2O near the subsolar point and by O_2 near the polar caps and the nightside. The models are able to yield reasonable abundance of O_2 in agreement with the observations, but the predicted H abundance is lower than reported by Barth et al. (1997). New measurements of atomic hydrogen can provide an important constraint for atmospheric models including atomic species.

In this study, we analyze the Lyman-α emission from nine STIS FUV observations, obtained from 1998 to 2014. Apart from the initial analysis by Feldman et al. (2000) of the 1998 data, the Lyman-α emission in the STIS images has not been investigated yet. The different orbital phases of Ganymede in the HST campaigns allow us to study potential hemispheric and temporal variability of the hydrogen corona.

In section 2, we describe the main characteristics of the observations used in this study. Section 3 deals with the methods used for the data processing as well as the modeling of the Lyman-α emissions. In section 4, we compare the STIS and modeled images, which allows us to estimate the contribution of the different sources of emission to the detected signal. Finally, section 5 deals with the implications of the results.

2. STIS images and observations

All analyzed STIS observations are carried out using the FUV-MAMA detector, the 52“ × 2” slit, and the G140L grating, which provides spatially and spectrally resolved images of Ganymede in a wavelength range between 1140 and 1730 Å. The angular resolution of each pixel in both x and y directions is 0.025 arcsec/pixel, and the spectral resolution corresponds to 0.584 Å/pixel.

Ganymede's diameter in the images varies within 1.58″ and 1.78″ between the HST campaigns, depending on the distance between the moon and the HST (see Table 1). The 2″ width of the slit in the x direction is sufficient to cover the entire disk and the pixel resolution corresponds to a spatial resolution of ~75 km at Ganymede. On the cross-dispersion axis, the 25″ large detector covers the moon's disk and its surroundings, allowing us to determine the background emissions (see Fig. 1). The observations we use in this study were made when Ganymede was near maximum elongation, obtaining images of either the trailing or leading hemispheres.

Depending on the geometry of the observation, the geocoronal emissions at Lyman-α constitute a strong contribution to the signal along the slit length. In order to minimize these geocoronal emissions, which complicate the analysis of the signal from Ganymede, we identify the exposures with geocoronal emissions at Lyman-α lower than 10 kR (Rayleigh, 1 R = $10^6/4\pi$ photons/cm^2/s/sr). Finally, in order to increase the signal to noise ratio (SNR), we combine these individual images for each of the visits (see Fig. 1A). To further increase the signal-to-noise ratio for the comparison of model and data, we generate 1-dimensional profiles along the cross-dispersion axis from the images, summing over d_G pixels in the x direction, where d_G stands for the diameter of Ganymede's disk in pixels (see Fig. 1B).

The STIS images taken during HST campaign 9296 are not reported in this paper due to the poor detected signal-to-noise ratio at the Lyman-α line. The observation was performed away from Jupiter opposition, resulting in high geocoronal emissions and a total background signal of ~22 kR. For comparison, in the other observations the brightness of the background is typically ~3 kR (see Table 2). As a result, the signal from Ganymede is faint compared to the strong background, and useful constrains on Ganymede's hydrogen corona, which is expected to emit a few hundred Rayleigh (Barth et al., 1997), cannot be derived for campaign 9296.

3. Model for the STIS images at Lyman-α

In order to understand the observed signal at Lyman-α in each of the observations, we model the different sources contributing to emission and absorption. We follow the modeling approach of Roth et al. (2017a), considering four essential sources of Lyman-α emissions: (a) scattered sunlight in the Earth's geocorona; (b) scattered sunlight by the interplanetary medium (IPM); (c) reflected sunlight from Ganymede's surface; and (d) scattered sunlight in Ganymede's atomic hydrogen corona.

The treatment of these emission sources is described in Sections 3.1–3.3. In Section 3.4 we derive the final model equation considering extinction of background emissions in Ganymede's corona. We finally present an approximation for potential extinction of Ganymede's corona signal in the Earth's upper atmosphere or geocorona, which affects the brightness of the corona signal detected by HST in Section 3.5.

3.1. Scattered light in the earth's geocorona and IPM

Scattered light in the Earth's geocorona and in the IPM are present along the whole slit at Lyman-α. However, while the geocoronal emissions originate in-between the HST and Ganymede, the fraction of the light scattered by the IPM behind Ganymede, as seen from the HST, is blocked by the moon's disk. In order to not overestimate the contribution from this source within Ganymede's disk, we differentiate between foreground and background emissions. The foreground emission is from the scattered light in the Earth's geocorona and in the IPM between the HST and Ganymede. On the other hand, the background emission is the scattered light in the IPM between Ganymede and infinity.

The IPM background brightness is calculated using the model of Pryor et al. (2008), which simulates the expected IPM brightness for a given viewing geometry. The values for this contribution at the different HST