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Galileo ultraviolet spectrometer observations of atomic hydrogen in the atmosphere of Ganymede

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Abstract. Atomic hydrogen Lyman alpha radiation (121.6 nm) has been measured in emission from the atmosphere of Ganymede with the Galileo ultraviolet spectrometer. An exospheric model with the following parameters has been fit to the observational data: atomic hydrogen density directly above the surface (radius 2634 km) equal to 1.5 x 10^4 atoms cm^{-3}, scale height 2634 km, exospheric temperature 450 K. A model calculation of the photodissociation of water vapor from surface ice at 146 K is used to obtain the photodissociation rate necessary to supply the hydrogen atoms that are escaping from the exosphere of Ganymede. The calculated escape flux of atomic hydrogen is 7 x 10^8 atoms/cm^2 sec. Two alternate but speculative sources of the atomic hydrogen escaping from Ganymede are photodesorption of water ice by ultraviolet photons in the wavelength range 120.5-186.0 nm and sputtering of water ice by Jupiter's magnetospheric ion plasma.

Introduction

Atomic hydrogen is present in the upper atmospheres of the Earth, Venus, and Mars. Its presence has been detected by measuring Lyman alpha radiation from the Sun that has been scattered by hydrogen atoms in the Earth's atmosphere [*Kupperian et al.,* 1959], in the atmosphere of Venus [*Barth et al.,* 1967], and in the atmosphere of Mars [*Barth et al.,* 1971]. For these three planetary bodies, the source of the atomic hydrogen is, directly or indirectly, the dissociation of water vapor in the atmosphere. For all three planets, atomic hydrogen is escaping from the top of the atmosphere by a variety of mechanisms including thermal or evaporative escape.

Since Ganymede has water ice on its surface, it is expected that there may be water vapor in the atmosphere above the water ice as a result of sublimation and that the water vapor will be photodissociated by solar ultraviolet radiation producing hydrogen atoms. A model calculation of the photochemistry of a water vapor atmosphere on Ganymede shows indeed that hydrogen atoms should be produced and that some fraction of them should escape from the gravitational field of Ganymede [*Yung and McElroy,* 1977]. There has also been the suggestion that charged particle bombardment of the surface of Ganymede should produce sputtering of water vapor from the surface ice and produce a water vapor atmosphere with a partial pressure that may be comparable to that produced by sublimation [*Lanzerotti et al.,* 1978].

Observations

The Galileo ultraviolet spectrometer (UVS) consists of a Cassegrain telescope and a Fastie-Ebert spectrometer [*Hord et al.,* 1992]. For the observations described in this paper, the field-of-view is 0.1 x 1.0 degrees and the grating is stepped through 16 steps up and down through the atomic hydrogen Lyman alpha line at 121.6 nm. Approximately equal amounts of time are spent measuring the emission line and the background. In the analysis of the data, the slit function was fit to the observational data using a least squares fit procedure. This technique successfully separates the emission line from the radiation noise that is produced in the photomultiplier tubes by the charged particles in Jupiter's magnetosphere.

During the Galileo flyby of Ganymede on June 27, 1996, the ultraviolet spectrometer scanned the atmosphere above the limb for seven minutes starting when the field-of-view was 2400 km above the limb and ending after the field-of-view had crossed onto the disk of Ganymede. At that time, the range to the limb was approximately 5700 km and the solar zenith angle was 60°. The sub-solar point was just south of the equator at a longitude of 170°. The limb crossing took place at a latitude of 21°S and a longitude of 226°W. The atomic hydrogen Lyman alpha line was measured 44 times during this seven minute limb observation period. Since the measurements were averaged in groups of four, the emission rate was determined every 225 km from a planetocentric distance (distance from the center of Ganymede) of 5000 km down to the limb (the radius of Ganymede is 2634 km). Figure 1 shows the emission rate in kiloRayleighs as a function of planetocentric distance. The Lyman alpha background of a nearby region of the sky (ecliptic latitude -31°, ecliptic longitude 345°) was measured several minutes after the limb observation and determined to be 0.61 kR with a statistical uncertainty of 0.04 kR. Using this measurement and a model [*Pryor et al.,* 1996], the emission rate of the

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Lyman alpha sky background in the direction of the limb observations (ecliptic latitude -21°, ecliptic longitude 305°) was determined to be 0.58 kR.

Exosphere Model

Since the density of the atmosphere of Ganymede is low, the analysis of data requires the use of exospheric theory. An exosphere is the region of planetary atmosphere where collisions between the neutral constituents essentially do not occur. The theory of the density distribution for a spherical atmosphere has been developed by *Chamberlain* [1963; *Chamberlain and Hunten*, 1987].

Figure 1 shows the result of an exosphere model fit to the Lyman alpha limb observations. This model was generated using an exospheric temperature of 450 K and a scale height of 2634 km. The figure also shows the Lyman alpha sky background of 0.58 kR. This model exosphere was fit to the data using a least squares fit procedure which gave a correlation coefficient of 0.42. One result of this fit is that the slant column emission rate at r = 2634 km (directly above the limb) is 1.14 kR with an uncertainty of 0.20 kR. Subtracting the 0.58 kR Lyman alpha background, the column emission rate attributed to the atmosphere of Ganymede is 0. 56 kR. Using an emission rate factor of 6.06×10^{-5} photons/sec-atom, a slant column density through the spherical atmosphere is determined to be 9.21×10^{12} atoms cm^{-2}. The emission rate factor is calculated using a measurement of the Lyman alpha solar flux at 1 AU by the SOLSTICE instrument on UARS (Rottman et al., 1993) of 3.02×10^{11} photons/cm^2 sec. The assumption is made that the flux in the center of the solar line is 3.02×10^{11} photons/cm^2 sec Å. This flux is adjusted to the mean distance of Jupiter at 5.205 AU. We also fit a 1/r function to the observational data using a least-squares fit procedure (correlation coefficient 0.46). As is shown in Figure 1, the 1/r function fits the observations as well as the exospheric model.

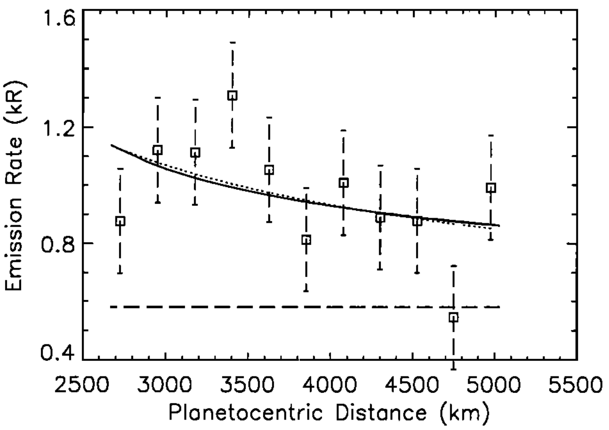

Figure 1. Observed emission rate of atomic hydrogen Lyman alpha emission from the atmosphere of Ganymede as a function of the distance from the center of Ganymede (squares). The error bars that are plotted on the data points show the statistical variation due to the signal and the radiation noise. The observations are fit with an exospheric model that has a temperature of 450 K (solid line). Also plotted is a 1/r fit to the observations (dotted line) and the Lyman alpha sky background (large dashes). The scatter in the data points is most likely caused by the radiation environment in Jupiter's magnetosphere.

Since the observations of the Lyman alpha emission rate are made by viewing the exosphere transversely from the outside, it is necessary to take into account the geometry of the spherical exosphere. As part of the development of the exospheric theory, *Chamberlain* has evaluated integrated-density functions for ballistic and escape orbits. Using the functions given in Tables IX.2 and IX.3 in *Chamberlain and Hunten* [1987], we calculate a volume density of 1.5×10^4 atoms cm^{-3} at r = 2634 km directly above the surface.

Escape Flux

Those hydrogen atoms that have a velocity greater than the escape velocity for Ganymede, 2.74 km/sec, and are moving upward have the opportunity to escape from the gravitational field of Ganymede if they do not undergo any further collisions. If the collision cross-section between the hydrogen atoms and the major constituent of the atmosphere is taken to be 3×10^{-15} cm^2, then the critical level occurs where the column density of the major constituent is 3×10^{14} cm^{-2}. This critical level is the exobase and the collisionless region above is the exosphere. The escape flux of hydrogen atoms from the exosphere is a function of the hydrogen atom density at the critical level, the most probable velocity of the atoms, v_m, and the energy parameter, λ_c, which appears in the exponent of the escape flux equation [*Chamberlain and Hunten,* 1987]. Using the parameters that were used to fit the atomic hydrogen distribution on Ganymede, T = 450 K, λ_c = 1, v_m = 2.74 km/sec, and assuming that the critical level is at r = 2792 km where the atomic hydrogen density is 1.2×10^4 cm^{-3} , the escape flux of atomic hydrogen is calculated to be 7×10^8 atoms/cm^2 sec.

Photodissociation and Photodesorption

A likely source of the hydrogen atoms in the atmosphere of Ganymede is the photodissociation of water vapor by solar ultraviolet photons of wavelength shorter than 242 nm which produces hydrogen atoms and hydroxyl radicals. A possible source of water vapor in the atmosphere is the sublimation of water ice on the surface. During the Galileo flyby of Ganymede, the photopolarimeter radiometer instrument (PPR) measured the 17-µm brightness temperature of the surface and found the maximum temperature to be 152 K [*Orton et al.*, 1996]. The Galileo near infrared mapping spectrometer (NIMS) which measured the depth of the water ice 2.0-µm band showed that water ice is non-uniformly distributed over the surface of Ganymede with more ice present in the polar regions (see Fig.7, *Carlson et al.*, 1996). Extensive analysis of the thermal properties of the ice on Ganymede suggests that the ice temperature may not be 152 K, but may be as low as 112 K [*Spencer,* 1987]. Ice at these temperatures would not have a vapor pressure high enough to provide a photodissociation rate large enough to support the calculated escape rate. A calculation using a photodissociation frequency of 1.7×10^{-7} sec^{-1} [*Yung and McElroy,* 1977] shows that 146 K is the lowest temperature where the photodissociation rate exceeds the calculated escape rate. For a model at 146 K, the vapor pressure of water is 2×10^{-8} mb, the column density of water molecules is 5×10^{15} molecules/cm^2, the exobase is at an altitude of 125 km (r = 2792 km) and the escape flux is 7×10^8 atoms/cm^2 sec.

A speculative source of the hydrogen atoms in the exosphere of Ganymede is the photodesorption of surface water ice. Since the atmosphere is thin, the solar ultraviolet radiation strikes the surface unattenuated. In the wavelength range 120.5-186.0 nm, the solar flux at Ganymede is 1.4×10^{11} photons/cm^2 sec. Photons in this wavelength range have energies between 6.7 and 10.3 eV. If 0.5% of the incident uv photons eject atomic hydrogen from the ice lattice, there would be a sufficient flux to supply the calculated escape flux of atomic hydrogen. Laboratory experiments on photodesorption show that water molecules are photodesorbed from water ice by Lyman alpha photons (energy 10.2 eV) with a yield of 0.7% at a temperature of 100 K [*Westley,* 1995]. Laboratory experiments on the bombardment of water ice by low-energy electrons show that atomic hydrogen (actually deuterium was used in the laboratory experiment) is desorbed from the ice starting at a threshold energy of 6.5 eV and that the yield of hydrogen atoms is larger than the yield of water molecules [*Kimmel and Orlando,* 1995]. Whether or not photons in the 6.7 to 10.3 eV energy range produce atomic hydrogen desorption is not known.

Ion Sputtering

Since Ganymede's orbit lies within the magnetosphere of Jupiter, the surface is constantly bombarded by the magnetospheric plasma that is corotating with Jupiter's magnetic field. Using data from Voyager measurements, the erosion rate of water ice from the surface of Ganymede has been calculated [*Johnson et al.,* 1982, *Johnson,* 1990]. Using the assumption that oxygen ions are the principal constituent of the magnetospheric plasma, the flux of water molecules from the surface of Ganymede is 1×10^{10} molecules/cm^2 sec. This is the same flux that occurs from sublimation of an icy surface at 125 K (Fig. 5, *Johnson et al.,* 1982). Thus, if ion erosion were the principal process producing a water vapor atmosphere, the partial pressure would be 2×10^{-11} mb. Photodissociation of such a water vapor atmosphere would be several orders of magnitude too low to account for the calculated escape flux of atomic hydrogen.

Another speculative source of the hydrogen atoms escaping from Ganymede is the ejection of hydrogen atoms directly from the surface ice by the impinging magnetospheric plasma ions. Jupiter's magnetospheric plasma was measured by the energetic particles detector (EPD) on the Galileo spacecraft [*Williams et al.,* 1992]. A calculation based on these observations gives an ion sputtering rate of 4.8×10^8 molecules/cm^2 sec [W. Ip, private communication]. Laboratory experiments on ion sputtering of water ice have shown that in addition to water molecules being eroded, molecular oxygen, molecular hydrogen, and atomic hydrogen are also ejected from the icy surface [*Bar-Nun et al.,* 1985]. If the sputtering yield of atomic hydrogen is high enough, then ion sputtering may be a viable source of the atomic hydrogen that is escaping from Ganymede.

For further speculation, we may compare the escape flux of atomic hydrogen calculated from the Galileo UVS observations of atomic hydrogen with the outward flow of hydrogen ions from Ganymede measured by the Galileo plasma instrumentation (PLS) [*Frank et al.,* 1997]. During the approach to Ganymede, the PLS measured a cold plasma of hydrogen ions with a density of 30 ions/cm^3 flowing outward at a velocity of 80 km/sec. This outward flow of hydrogen ions of 2×10^8 ions/cm^2 sec is similar in magnitude to the calculated escape flux of hydrogen atoms, 7×10^8 atoms/cm^2 sec. One of the suggestions for the source of the cold hydrogen ions is ion impact on the water ices on the surface of Ganymede [*Frank et al.,* 1997]. If indeed the ion bombardment of the surface ice of Ganymede is the source of hydrogen ions flowing outward, then it is plausible to suggest that this same ion sputtering may be producing hydrogen atoms with a similar yield. There are no laboratory experiments that have measured hydrogen ions being ejected from icy surfaces by ion sputtering.

Oxygen

If the escaping hydrogen atoms are produced by the photodissociation of water in the atmosphere, the hydroxyl radicals that are produced may stick to the surface ice. The sticking coefficient of OH on ice has been measured in the laboratory and found to be 0.03 [*Cooper and Abbatt,* 1996]. On Ganymede, the OH radicals would have many collisions with the surface and gradually accumulate in the ice. If the hydrogen atoms are directly ejected from the ice, the hydroxyl radicals would remain in the ice and have the opportunity to react and form various compounds of oxygen and hydrogen The amount of ice that is lost because of the escape of atomic hydrogen may be calculated using the escape rate determined from the Galileo ultraviolet spectrometer measurements of atomic hydrogen. Taking into account the day-night cycle on Ganymede, the average thickness of water ice that is lost is 1 nm per year. Since hydrogen atoms are escaping, it is oxygen in some form that is accumulating in the ice. It may be noted that molecular oxygen and ozone are observed in the ice of Ganymede [*Spencer et al.,* 1995; *Calvin et al.,* 1996; *Noll et al.,* 1996]. There may be a small amount of molecular oxygen in the atmosphere of Ganymede. A column density of $(1\text{-}10) \times 10^{14}$ oxygen molecules cm^{-2} has been inferred from an analysis of HST observations of the ultraviolet airglow of Ganymede [*Hall et al.,* 1997].

Uncertainties

The calculation of the escape flux is model dependent. The value of 7×10^8 atoms/cm^2 sec was calculated for a model in which the hydrogen atoms are produced by photodissociation in an atmosphere with a temperature of 450 K and the atmospheric density is sufficiently high to form an exobase at 125 km. If the hydrogen atoms are ejected from the surface with excess kinetic energy, then the escape flux may be greater than 7×10^8 atoms/cm^2 sec. For either mechanism, the density of the neutral atmosphere is the important parameter since it determines whether or not the hot atoms equilibrate before escaping.

Summary

Atomic hydrogen has been measured in the atmosphere of Ganymede. The density directly above the surface is 1.5

x 10^4 atoms cm^{-3}. The altitude distribution may be described by a scale height that corresponds to a temperature of 450 K. A possible source of the atomic hydrogen is the photodissociation of water vapor that has sublimed from the ice on the surface. Using the water vapor atmosphere model, the escape flux of atomic hydrogen is calculated to be 7 x 10^8 atoms/ cm^2 sec. However, to supply this amount of atomic hydrogen from photodissociation of water vapor, there needs to be a substantial reservoir of ice on the surface that is at a temperature of 146 K or higher. While the hydrogen atoms that are produced from the dissociation of water have the opportunity to escape, the oxygen atoms tend to remain behind. The amount of water ice that is consumed in producing the escaping hydrogen atoms is 1 nm per year. The amount of oxygen that accumulates on Ganymede should be nearly equal to that same equivalent column.

There are two additional possible sources of the hydrogen atoms that are observed in the atmosphere of Ganymede. They are the photodesorption of water ice by solar photons in the far ultraviolet wavelength range and the sputtering of water ice by Jupiter's magnetospheric ion plasma.

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