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Evidence for short cooling time in the Io plasma torus

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Abstract. We present empirical evidence for a radiative cooling time for the Io plasma torus that is about a factor of ten less than presently accepted values. We show that brightness fluctuations of the torus in the extreme ultraviolet (EUV) at one ansa are uncorrelated with the brightness at the other ansa displaced in time by five hours, either later or earlier. Because the time for a volume of plasma to move from one ansa to the other is only five hours, the cooling time must be less than this transport time in order to wipe out memory of the temperatures between ansae. Most ($\sim 80-85\%$) of the EUV emission comes from a narrow (presumably ribbon-like) feature within the torus. The short cooling time we observe is compatible with theoretical estimates if the electron density in the ribbon is $\sim 10^4/\mathrm{cm}^3$. The cooling time for the rest of the torus (which radiates the remaining 15-20% of the power) is presumably consistent with the previously derived 20-hour values. A nearly-continuous heating in both longitude and time is needed to maintain the EUV visibility of the torus ribbon – a requirement not satisfied by presently available theories.

Introduction

The Io plasma torus radiates power at the rate of a few times 10^{12} W [Sandel et al., 1979; Hall et al., 1995], which makes it an energetically significant component of the Jovian magnetosphere. Its radiative cooling time is important for understanding the magnetospheric power budget. In order that the plasma torus brightness remain approximately constant, energy must be resupplied on a time-scale of the order of or shorter than the cooling time. Thus, by determining the cooling time, we also gain some insight into requirements for energy-input mechanisms and power budget for the plasma torus.

There are two standard theories of the power source for the plasma torus: (1) The neutral cloud theory, in which power is drawn from pick-up energy of sulfur and oxygen from Io, both newly ionized by electron impact and re-energized by charge-exchange [Broadfoot et al, 1979; Barbosa, 1994], and, (2) inward transport of hotter plasma from the plasma sheet [Smith et al., 1988; Herbert and Sandel, 1995]. These mechanisms were modeled to a torus having a long ($\sim$ 20 hour) radiative cooling time. However, in examinations of Voyager 2 Ultraviolet Spectrometer (UVS) data, Dessler and Sandel [1992, 1993] and Sandel and Dessler [1993] concluded that the cooling time is significantly shorter. Here, using an improved version of these UVS data, we show that the cooling time is approximately two hours, an order-of-magnitude less than the presently accepted value.

Results

During a 40-day observation period, while inbound to its 1979 Jupiter encounter, Voyager 2 UVS scanned the Io torus over 75 rotations of Jupiter, nominally scanning the plasma torus five times during each Jovian rotation. A complete scan from one ansa to the other took one hour. We analyze 685 Å emission, which comes mainly from S^{++}. The intensity of emission in these lines is proportional to the product of ion and electron number densities and is an approximately exponential function of electron temperature. The brightest point recorded at each ansa is a radially confined feature with a width of no more than about 0.2 R_J [Dessler and Sandel, 1993]. We have repeated their fits for six system scans, which showed eight usable brightness profiles. From these eight profiles we were able to fit six with ribbon FWHM of 0.22 R_J or less. We refer to this bright feature as the "ribbon" after its appearance at optical wavelengths, although ribbons observed at such different wavelengths are likely not coincident in space.

Reproducible periodic brightness variations have been discovered in the EUV: namely, the Io phase effect [Sandel and Broadfoot, 1982] and the System IV period [Sandel and Dessler, 1988]. Because these variations are not relevant to torus cooling time and would confuse the present study, their average effects have been removed. The UVS data have been improved for this study over those used by Sandel and Dessler [1993] by (a) allowing for the 36° change in System III longitudes during the hour required for the UVS slit to sweep from one ansa to the other, and (b) making a better subtraction of the brightness variations associated with the orbital motion of Io (the Io phase effect) by taking into account its dependence on System III longitude.

Optical observations [e.g., Schneider and Trauger, 1995] in S^+ show a torus ribbon that is not "lumpy"

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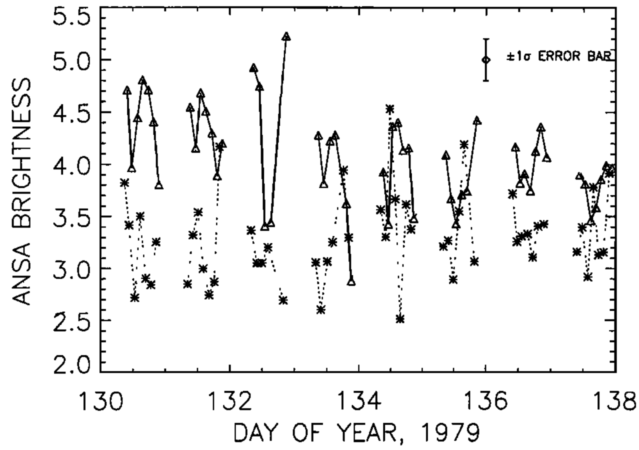

Figure 1. The apparent brightness of the receding (Δ) and approaching (*) ansa at 685 Å over 8 days. The averages of the Io phase effect and System IV variations have been removed. The spacing between the points is 2 hours, except for daily gaps. The rapid variations in emission intensity imply longitudinally-variable electron temperatures in the plasma torus.

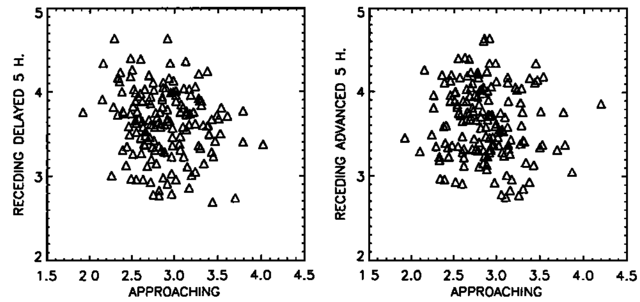

Figure 2. The emission brightness of the approaching plasma torus ansa (in arbitrary units) versus the emission of the receding ansa 5 hours later and 5 hours earlier. If the cooling time of the plasma torus were 5 hours or longer, the plasma temperature and thus brightness should be correlated. No such correlation is seen, implying that the cooling time is less than 5 hours.

down to a scale as small as $\sim 20°$ in System III longitude. In contrast, as shown in Fig. 1, the ribbon, as seen by UVS in S^{++} on a 70° scale, flashes and sparkles. The receding (approaching) ansae mean intensity $\bar{I}$=4.07 (3.20) with a standard deviation σ=0.41 (0.38). Changes of 20% or more in brightness are common (see Fig. 1). Because S^{++} is derived from S^{+}, and because emissions in the longer optical wavelengths are insensitive to variations in electron temperature but vary as the square of the plasma number density, we argue that the number density of S^{++} ions in the torus must also be a smoothly varying function of System III longitude. (No significant System III variations in the UVS data are seen because of the differences in field of view between the EUV and optical observations [Brown, 1995; Schneider and Trauger, 1995].) We conclude that the variations in emission intensity of the UVS data on time-scales as short as 2 hours is, therefore, caused by variations with longitude of electron temperature in the ribbon.

We exploit the above attributes of the ribbon in the Io plasma torus – a ribbon that is longitudinally smooth in plasma number density but displaying longitudinal irregularities in electron temperature. We define the cooling time as the time for a plasma parcel, in the absence of any energy inputs, to radiate all but $1/e$ of its initial electron kinetic energy. This is equivalent to saying that the cooling time is the ratio of the electron kinetic energy within a plasma parcel to the power radiated from this parcel. The brightness of an isolated segment of the ribbon falls to $1/2e$ of its initial value in a time equal to the cooling time.

If the cooling time were as long as 20 hours, as suggested by theoretical estimates [e.g. Barbosa, 1994; Shemansky, 1988], electron temperature values should persist as torus plasma is transported from one ansa to the other. One should expect a correlation between ansae observed only 5 hours apart. Figure 2 shows that there is no such correlation: the brightness, and thus the electron temperature, of one ansa of the torus is independent of the brightness of the other ansa 5-hours earlier or later.

We can support the above conclusion using synthetic data sets to demonstrate the influence of the cooling time on emission intensity. We have performed a number of tests, and we show a representative result. Fig. 3 shows the result for a torus with a constant heating source that maintains the average torus temperature and a second superposed random source having a mean of 0 and a standard deviation of 1. We show the results for respective cooling times of 2, 4, and 20-hours. For a 2-hour cooling time, there is no correlation between the energy contents of the ansae, whereas for a 20-hour cooling time, the smoothing effect of the long cooling time leads to an obvious correlation between the two ansae. A slight correlation is evident for even a 4-hour cooling time.

We have done other simulations with random times (range: $0 \leq$ time ≤ 6 hours) during which a random heating is applied (range: $0 \leq$ power ≤ 2 average source, where the average source is that necessary to keep the torus at its average temperature). In numerous runs, we have not been able to create an uncorrelated dataset that looks like that of Fig. 2, unless the cooling time is less than the 5-hour ansa to ansa transport time. These simulations lead us to an estimated upper limit for the cooling time of 3 hours, with 2 hours being our preferred value.

Discussion

The 2-3 hours cooling time we derive implies higher densities in the ribbon feature of the Io plasma torus than previously thought. The energy content per unit volume of the plasma torus increases linearly with electron density, while the radiative output per unit volume increases as the product of the electron and ion densities, so the cooling time, which we defined as the electron energy content divided by the radiative output, is inversely proportional to the electron concentration. Shemansky [1988] and Barbosa [1994] calculated cooling times of approximately 20 hours for an electron concentration of $2 \times 10^3/\text{cm}^3$. We do not perform an independent calculation of the cooling time. Instead, we adopt Shemansky's and Barbosa's results, and we scale their electron concentration as inversely proportional to the cooling time. For a 2-hour cooling time, the electron concentration in the region responsible for the bulk of the EUV emission is thus 10 times greater than they assumed, or $2 \times 10^4/\mathrm{cm}^3$.

Recent analysis of the spatial motion of the emission seen by the UVS also requires such high electron concentrations in order to account for the $\sim 85\%$ radiative power contribution of the ribbon with its limited radial thickness of no more than 0.2 R_J [Dessler and Sandel, 1993]. If we assume a height of ± 0.5 R_J and a ribbon location of 5.9 R_J, the upper limit to the total volume of emission is therefore 7 $R_J{}^3$, or 2.5×10^{30} cm^3, requiring a power output density of at least 9×10^{-19} $\mathrm{W/cm}^3$, for a total power output of 3×10^{12} W. The model of Barbosa [1994] gives a power-output density of 0.2 $\mathrm{eV/cm^3}$-s for an electron concentration of $2000/\mathrm{cm}^3$. To increase this output density by 30 or more calls for an increase in electron number density by a factor $\sqrt{30}$ to $1 \times 10^4/\mathrm{cm}^3$, which is consistent with the electron density derived in the previous paragraph to account for a 2-hour cooling time. Such an electron concentration is higher than inferred from previous ground-based observations [Brown et al., 1983; Morgan, 1985]. We suggest that the lower estimate of plasma number density obtained using remote sensing data may be caused by line-of-sight averaging and longitudinal variations in the plasma torus.

There is some observational support for such a dense ribbon. The Voyager PRA data showed a spike in electron density of $3500/\mathrm{cm}^3$ at 5.7R_J [Warwick et al., 1979]. The time resolution of their instrument, however, was 6 minutes so that a denser peak could have been missed. Gurnett et al. [1996] found a peak electron density of $4 \times 10^4/\mathrm{cm}^3$during the recent flythrough of the Io wake by Galileo, but no separate ribbon-like structure has been reported [Bagenal, 1996]. We suggest that the ribbon was very near Io at the time of the torus flythrough and was not a detectable, separate feature. We suggest that the ribbon both contributed to and became assimilated within the Io wake.

With a 2-hour cooling time, EUV emissions from the ribbon would be even more erratic than shown in Fig. 1 if the electrons were not resupplied with energy on a similar time-scale. The UVS data show that a typical maximal dimming of a ribbon element is 30% in 5 hours (see Figs. 1 and 2), which implies a maximal temperature difference of 15%. If we wished to ascribe the erratic nature of the EUV ribbon brightness to gaps in ribbon heating, such that there was no heating for a time t, the ribbon temperature would decrease by a factor $e^{-t/\tau}$. For a cooling time $\tau = 2$ h and a temperature difference of 15%, $t = 0.35$ h. This means that no element of the ribbon went for more than 0.35 hours, or 12° of longitude, without heat being applied. The heating of the ribbon is, therefore, quasi-continuous in time and longitude. There is additional heating associated with Io to account for the Io phase effect [Sandel and Broadfoot, 1982]. However, the requirement of nearly-continuous background heating rules out any simple mechanism utilizing either Io or a gas cloud spatially associated with Io, because Io and its gas cloud revisit each part of the torus only once every 13 hours.

Heating of ribbon electrons must be a function of local time, as pointed out by Dessler and Sandel [1992, 1993]. The heating of electrons in the ribbon reaches a peak near the dusk side in order that there be a persistent difference in brightness of the receding over the approaching ansae as discovered by the Voyager 2 UVS (the dawn-dusk effect). The difference in brightness of the ansae as seen in ground-based observations [e.g., Schneider and Trauger, 1995] is not explained by an electron temperature difference, because brightness at these longer wavelengths is not sensitive to temperature. Instead, the brightness asymmetry at these longer wavelengths is quantitatively accounted for by a difference in plasma number density at the two ansae [Dessler and Sandel, 1992].

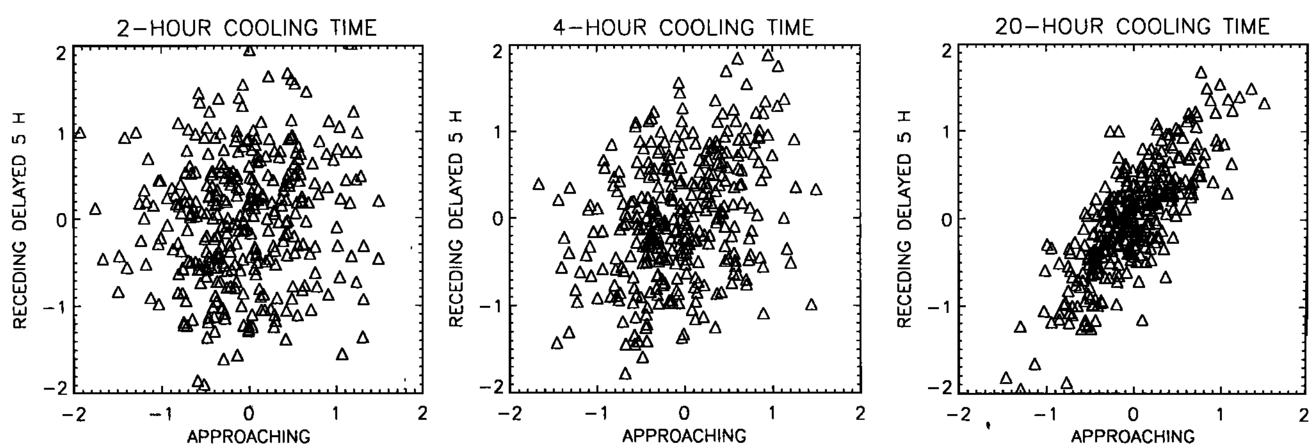

Figure 3. Synthetic data showing the difference for the ansae brightness for cooling times of 2, 4, and 20 hours. Heat is applied to the torus elements erratically, as described in the text. The data are normalized to the center of the plot (0,0). The model for a 2-hour cooling time shows scatter similar to that of the Voyager data. The test using a 20-hour cooling time shows significant correlation between the two ansae 5-hours apart, which is not in agreement with the Voyager data. A cooling time as short as even 4 hours shows some correlation.

Conclusions

Because of a lack of correlation between the EUV brightness at one ansa of the plasma torus and the brightness at the opposite ansa 5 hours earlier or later, we conclude that, at the time of the Voyager 2 fly-by, the cooling time of the ribbon (the region of the Io plasma torus that radiates most of the EUV power) is approximately 2 hours, with an upper limit of 3 hours. Such a cooling time requires an electron concentration in the ribbon of $\sim 10^4/\text{cm}^3$, about a factor of 10 greater than used in earlier theoretical estimates of the cooling time. The 30% excess brightness of the receding ansa over the approaching ansa as seen by the Voyager 2 UVS, requires 30% extra power input to the brighter ansa [Dessler and Sandel, 1992]. It is not explained by a higher plasma density at the receding ansa. The short cooling time and relatively constant brightness of the ribbon in the plasma torus implies that energy input into the ribbon contains no gaps larger than 12° in longitude or longer than 0.35 hours in time. There is no direct experimental measurement of the cooling time in the rest of the torus, which radiates the remaining 15 - 20% of the EUV power; we have no quarrel with the published estimated of $\sim$ 20 hours. Finally we note that, although the power source for the ribbon varies with local time to produce the dawn-dusk effect, this power source is not directly related to the position of Io. The Io phase effect, which involves less power, is, of course, connected to Io. The physical nature of neither the Io nor the non-Io power sources have been revealed to us by this study.

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