towards the Sun, perhaps due to a decrease in the external solar wind pressure. We must conclude that the extrapolation process for Voyager 2 is not well defined in that region and the general agreement throughout the passes seems to be better than could be explained by chance. The situation remains speculative but warrants examination by other means.

Columbo pointed out that the positions of the maxima surrounding the $L \simeq 14$ dip could represent regions where the equatorial absorbing material has been cleared out by resonances with Titan's orbital period (3:2 at 15.5 R_s and 2:1 at 12.8 R_s).

We conclude that the plasma experiments on Voyager 1 and 2 and on Pioneer 11 show outer magnetospheric structure at the same position in L. The observations suggest the presence of absorbers in the equatorial plane whose nature may be debris or possibly gas. It would be interesting to see if the presence of this material could be detected by direct observations of scattered light or by stellar occultation experiments.

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An interpretation of the dawn–dusk asymmetry of UV emission from the Io plasma torus

W.-H. Ip & C. K. Goertz

Max-Planck-Institut für Aeronomie,
D-3411 Katlenburg-Lindau 3, FRG

Recently, the Voyager UVS experimenters made two interesting reports on the emission morphology and energetics of the Io plasma torus. First, Sandel and Broadfoot[1] provided evidence for a localized energy source in the vicinity of Io with the time-averaged power amounting to 20% of the total power radiated by the Io UV torus. Second, Shemansky and Sandel[2] demonstrated that the Io torus displays a local time variation in the extreme UV (EUV) emissions with a dawn-to-dusk asymmetry differing by ~30% and that the corresponding electron energy density available for exciting the UV emissions of the oxygen and sulphur ions varies by ~20%. These observations provide an important insight into the mass and energy flows of the Io plasma, but call into question our understanding of the physical mechanisms that maintain the radiative emissions of the heavy ions ejected from Io. Here we discuss the physical cause of the brightening near dusk side and dimming near dawn side of the Io plasma torus EUV emissions in terms of a drift shell effect. If the radial distance of the L shell of the Io plasma torus reaches a minimum around 1800 h LT but reaches a maximum around 0600 h LT, periodic adiabatic heating and cooling of the electron gas could lead to the observed modulation of the UV irradiation. Such a drift pattern of the Io torus could be produced if the plasma convection of the jovian magnetosphere were partly determined by its planetary wind outflow.

After the Voyager observations of Jupiter, the major issue concerns how to relate the auroral emissions near the footpoints of the Io torus to the UV emissions of the Io torus itself. An apparent consensus[3–5] is that the auroral emission is caused by the atmospheric precipitation of energetic protons and heavy ions which in turn produces a flow of secondary electrons beaming back into the Io plasma torus. These secondary electrons of energies $\geqslant$10–20 eV could provide the required heat source for the torus electrons if the precipitating flux of heavy ions having energies $\leqslant$500 keV is intense enough[5]. Other electron acceleration mechanisms could also be important. For example, the energy transfer from the new ions created by charge exchange between the co-rotating thermal ions and the neutral atoms[6–8] to the electrons could be significant[9–11]. This might mean that there exists strong interaction between the electrons and electrostatic or electromagnetic plasma waves even though these effects have not been well established by observations.

By the same token, wave-particle scattering and electrostatic acceleration processes in the vicinity of the Io flux tube might be particularly strong to enhance the atmospheric precipitation of energetically charged particles as well as injection of suprathermal electrons into the co-rotation wake of Io. Note that the total current of 3×10^6 A flowing along the Io flux tube[12] implies a power of 2×10^{11} W as a result of the unipolar induction mechanism of Io in the jovian magnetosphere. If this current is carried mainly by suprathermal electrons[13,14], local dissipation of this power would lead to the Io-related hotspot of UV emissions as investigated by Sandel and Broadfoot[1]. The local time variation of the Io torus emissions[2], however, could not be interpreted in this manner, because precipitation of energetic particles by pitch-angle scattering into loss cone presumably extends throughout the whole torus without longitudinal restriction[15–17]. This view is partially supported by the Voyager observations of the continuous distribution of the auroral emissions magnetically connected to the Io torus[10,18]. There is difficulty, therefore, in relating the secondary electron heat flow effect to the conclusion[2] that the dawn–dusk asymmetry is caused by a maximum of energy injection into the Io torus at local noon.

One possible alternative is to assume that the energy injection rate into the Io plasma torus is approximately the same for all local times but that the excitation rate of the UV emissions is maximized at the dusk side and minimized at the dawn side. This could be achieved if the drift shell of the Io plasma torus has varying L values for different local times as periodic adiabatic expansion and compression of the flux tubes would allow the energy flux to the UV irradiation to be modulated in the desired direction.

In an attempt to invoke soft electrons as a heat source for Jupiter's thermosphere, Hunten and Dessler[19] have made the interesting point that inward convection of a magnetic flux tube containing N electrons from a radial distance L_1 to L_2 leads to the enhancement of the corresponding omnidirectional energy flux (Q) by a factor of $(L_1/L_2)^8$. Briefly, the volume V of a magnetic flux in a dipole field varies as L^4: $V \propto L^4$. If the ratio of specific heats $\gamma = 5/3$, the electron thermal energy ε can be given as:

$$\varepsilon \propto V^{1-\gamma} \propto L^{-8/3} \qquad (1)$$

Now, for $Q = nu\varepsilon$ where the particle velocity $u \propto \varepsilon^{1/2}$ and $n = N/V$ we find directly

$$Q_2 = Q_1(L_1/L_2)^8 \qquad (2)$$

Thus for Q_2 to be larger than Q_1 by ~20%, as indicated by the UV observations of the Io plasma torus[2], we need $L_1/L_2 \sim 1.02$ or the radial distances at the dusk side (smaller) and the dawn side (larger) to vary by ~±1%. To produce such a shift of the drift shell of the Io plasma torus, an electric field (E_i) directed from dawn to dusk superimposed on the co-rotation electric field (E_c) is required. For a magnetic field of ~2,000 nT and a co-rotation speed of 80 km s^{-1}, the co-rotation electric field at Io's orbit is 0.16 V m^{-1}. The magnitude of this cross-tail electric field therefore should be ~1.6 mV m^{-1}.

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As discussed by Goertz and Ip[20], an electrostatic field of such nature can be established by a magnetosphere convection system driven by the jovian planetary wind or outflow of heavy ions emitted from Io. The initial assessment by Brice and Ioannidis[21] is that, because of its rapid rotation and strong dipole field, the jovian magnetosphere has predominantly the configuration of a co-rotating plasmasphere. (This theoretical idea has been qualitatively confirmed by the Voyager plasma experiments[22–24].) Besides such a co-rotation convection system, Brice and Ioannidis[21] also discussed the presence of a plasma flow in the magnetotail directed towards the planet, driven by the solar wind interaction[25]. In this case, however, the resulting cross-tail electric field would point from dusk to dawn, and would produce a dawn–dusk asymmetry of the UV emissions in the Io plasma torus that was the opposite of the observations. The existence of a planetary wind outflow based on theoretical considerations[26,27] and Voyager observations[24] introduces the possibility that the actual cross-tail electric field could be reversed, producing the required Io plasma torus drift shell displacement.

Note that, under the assumption of uniform energy injection rate along Io's orbit, the idea presented here is not invalidated by the non-dipole nature of the jovian magnetic field[28,29]. This is because the thermal ions under consideration basically co-rotate with the magnetic field; without an externally applied electric field, there will be no change in the field strength at different local times. Thus, the only effect of periodic adiabatic heating–cooling must originate from the dawn-to-dusk electric field.

Thus, the interpretation of the local time variation in the UV emissions of the Io plasma torus must be constrained by the thermodynamic and electrodynamic couplings of the Io torus to the corresponding auroral zone; circumstantial evidence seems to exclude any drastic variation of the energy injection rate into the Io plasma torus between local noon and local midnight. In these conditions, a possible solution is to invoke the periodic heating and cooling of the electron gas in the Io plasma torus as a result of a slightly eccentric dipole drift shell. The proper modulation of the UV excitation rate can be obtained by the presence of an electrostatic field of $\sim 1.6\,\mathrm{mV\,m^{-1}}$ pointing from dawn to dusk. Such an electric field pattern is expected if the plasma convection in the jovian magnetosphere is determined by the outflow of its planetary wind. Conversely, the UV observations reported by Shemansky and Sandel[2], in principle, can be diagnostic of the magnetospheric convection system.

After completion of this manuscript, we learned that Barbosa and Kivelson[30] have independently reached a similar conclusion on the physical cause of the dawn–dusk asymmetry of the Io plasma torus UV emission.

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Beginning and end of lunar mare volcanism

P. H. Schultz

Lunar and Planetary Institute, 3303 NASA Road 1, Houston,
Texas 77058, USA

P. D. Spudis

Department of Geology, Arizona State University, Tempe,
Arizona 85287, USA

Mare volcanism on the Moon is commonly attributed to an important but relatively short-lived epoch of internal heating after 3,900 Myr BP but before about 2,500 Myr BP (refs 1, 2). Although some studies suggested that mare volcanism had started earlier[3–5] than times indicated by dated lunar samples, only recently have photogeological, spectral, and geochemical data[6–8] documented the importance of a pre-4,000 Myr BP epoch. Similarly, early Earth-based geological mapping revealed a bright-rayed crater (Lichtenberg) superposed by mare units[9], thereby indicating that mare volcanism must have extended to times significantly more recent than 3,100 Myr BP. Lunar orbital photography confirmed this inferred stratigraphical relationship[10], but crater statistics indicated that the youngest units were at least twice the age of Copernicus, or between 1,700 and 2,000 Myr BP (refs 11–13). We present here the inferred distribution and style of the early phases of mare volcanism based on current evidence and conclude that certain regions of the Moon underwent two distinct pulses of igneous activity. We then examine crater statistics for the post-Lichtenberg mare unit and other selected units and conclude that mare volcanism extended to a time comparable with that of the Copernicus impact, or ~1 Myr BP. These reassessments of the oldest and youngest maria provide new constraints on geophysical models of the internal thermal history of the Moon.

Direct evidence for the existence of ancient lunar volcanism is found in a variety of sample investigations. Numerous mare basalt fragments are found as clasts in breccias that were assembled before 3,900 Myr BP (refs 14, 15). Many of these breccias appear to be related to major basins, suggesting that volcanic flows constituted at least part of the target for these impacts. Such volcanics could have existed either as lava flows covering the basin impact site or subsurface magma reservoirs ejected and subsequently included in basin deposits. Mixing model studies of highland soils (see ref. 16) require substantial admixture of a mare basalt component at a level significantly higher than that expected from post-mare lateral mixing by impacts[17]. This suggests the presence of a mare component within the highlands, either buried by and included within highlands megaregolith or deposited as basin ejecta.

The very early stages of mare volcanism are believed to be indicated by dark-haloed impact craters which have excavated ancient mare units from below light-coloured ejecta deposits[6]. More than 100 such craters larger than 1 km in diameter have been identified on the Moon. Apollo orbital geochemical data[6,8] and recent Earth-based spectral data[7] confirm the proposed mafic component in these ejecta. The distribution of dark-haloed impact craters can provide a basis for mapping buried mare basalt plains in order to understand the areal extent and the source regions. Figure 1 illustrates a conservative estimate

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