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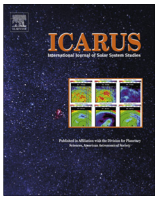

Incomplete cooling down of Saturn's A ring at solar equinox: Implication for seasonal thermal inertia and internal structure of ring particles

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ABSTRACT

At the solar equinox in August 2009, the Composite Infrared Spectrometer (CIRS) onboard Cassini showed the lowest Saturn's ring temperatures ever observed. Detailed radiative transfer models show that the observed equinox temperatures of Saturn's A ring are much higher than model predictions as long as only the flux from Saturn is taken into account. In addition, the post-equinox temperatures are lower than the pre-equinox temperatures at the same absolute solar elevation angle. These facts indicate that the A ring was not completely cooled down at the equinox and that it is possible to give constraints on the size and seasonal thermal inertia of ring particles using seasonal temperature variations around the equinox. We develop a simple seasonal model for ring temperatures and first assume that the internal density and the thermal inertia of a ring particle are uniform with depth. The particle size is estimated to be 1–2 m. The seasonal thermal inertia is found to be 30–50 $\mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$ in the middle A ring whereas it is $\sim$10 $\mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$ or as low as the diurnal thermal inertia in the inner and outermost regions of the A ring. An additional internal structure model, in which a particle has a high density core surrounded by a fluffy regolith mantle, shows that the core radius relative to the particle radius is about 0.9 for the middle A ring and is much less for the inner and outer regions of the A ring. This means that the radial variation of the internal density of ring particles exists across the A ring. Some mechanisms may be confining dense particles in the middle A ring against viscous diffusion. Alternatively, the (middle) A ring might have recently formed ($<10^8$ yr) by destruction of an icy satellite, so that dense particles have not yet diffused over the A ring and regolith mantles of particles have not grown thick. Our model results also indicate that the composition of the core is predominantly water ice, not rock.

1. Introduction

Saturn's main rings consist of many small particles orbiting around the planet. The range of particle sizes deduced from radio and stellar occultations is roughly 1 cm to 10 m (Zebker et al., 1985; French and Nicholson, 2000; Cuzzi et al., 2009). The composition of ring particles is mostly crystalline water ice and the mass fraction of contaminants (e.g., Tholins, PAHs, or nanohematite) is 10% at most (Epstein et al., 1984; Cuzzi et al., 2009) and probably less than 1% (Poulet et al., 2003). A favorable origin of Saturn's rings with such a high content of water ice is stripping of the icy mantle of a Titan-sized satellite (Canup, 2010). This hypothesis indicates that Saturn's rings are primordial (as old as Saturn itself) and the initial mass was a few order of magnitude more massive than the present ring mass. As a byproduct of viscous diffusion of Saturn's rings, accretion of icy satellites occurs at the outer edge of the rings, followed by orbital expansions of the satellites due to the torques exerted by the rings and the planet (Charnoz et al., 2010, 2011).

While the ring system as a whole may be primordial, local structures of the rings generally change on much shorter timescales. Particularly, several observational facts indicates that the outermost main ring, the A ring, is dynamically young (see Charnoz et al., 2009 for the review). The A ring extends from 122,000 km to 137,000 km from the center of Saturn. Gravitational torques exerted at resonances in the A ring with inner icy satellites, such as Mimas, Janus, and Epimetheus, cause the A ring to collapse to its inner edge in $\sim 10^8$ years (Goldreich and Tremaine, 1982; Dones, 1991), unless angular momentum is supplied from some other sources. The A ring viscosity measured from density wave patterns at satellite resonances is of the order of 100 $\mathrm{cm^2\,s^{-1}}$ or higher (Esposito et al., 1983; Tiscareno et al.,

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2007). This also gives a radial diffusion timescale of $\sim 10^8$ years for the A ring width (see also Salmon et al., 2010). The high viscosity of the A ring is likely a result of wakes produced by gravitational agglomeration of ring particles. Self-gravity wakes are observationally suggested from azimuthal brightness asymmetry (e.g., Dones et al., 1993; French et al., 2007; Colwell et al., 2006; Hedman et al., 2007; Ferrari et al., 2009) and also predicted from *N*-body simulations (Salo, 1995; Daisaka et al., 2001; Salo et al., 2004; Robbins et al., 2010). The apparently young A ring may or may not be compatible with the primordial origin of the ring system. To clarify the origin and evolution of the ring system, additional observational constraints are invaluable.

Since Saturn Orbit Insertion of Cassini in 2004 to the present, the Cassini spacecraft has been observing Saturn's rings in broad wavelengths from ultraviolet to radio. The Cassini Composite infrared Spectrometer (CIRS) has acquired millions of ring spectra in mid- to far-infrared wavelengths (7 μm to 1 mm) at various observational geometries (e.g., Spilker et al., 2006; Altobelli et al., 2008, 2014; Leyrat et al., 2008b). The wavelength range of CIRS covers the Planck peak of the thermal emission, and the effective temperature and the geometric filling factor of a ring are derived by applying a Planck fit to a spectrum (see Spilker et al., 2006 for details). The typical error in the derived temperature is much less than 1 K.

Ring temperatures depend on observational geometric parameters. Ring temperatures vary seasonally primarily due to the change of solar elevation angle from $-27°$ to $27°$ and secondarily due to the change of heliocentric distance of Saturn (Froidevaux, 1981; Flandes et al., 2010; Pilorz et al., 2015). The face illuminated by the Sun (the lit face) is warmer than the unlit face and the difference between the lit and unlit face temperatures increases with ring optical depth (Spilker et al., 2006). Ring temperatures also vary diurnally due to eclipse cooling in Saturn's shadow (Leyrat et al., 2008b). On top of the eclipse cooling, the temperatures of the A ring show quadruple azimuthal modulations due to self-gravity wakes (Leyrat et al., 2008b). Ring temperatures increase with decreasing solar phase angle (Altobelli et al., 2007, 2009), indicating that ring particles are not isotropic emitters.

With each temperature variation, different types of constraints on ring structures and particle properties are obtained. For example, the diurnal thermal inertia of ring particles is estimated to be $\sim 10\ \mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$ for all main rings, using diurnal temperature variation curves including temperatures in Saturn's shadow (Ferrari et al., 2005; Leyrat et al., 2008a; Morishima et al., 2011, 2014). This low thermal inertia value indicates that surface regolith of ring particles is very fluffy at least for the thickness comparable to the diurnal thermal skin depth, ~1 mm. However, fluffiness of deep interiors of ring particles cannot be constrained from diurnal temperature variations. Very porous regolith on the particle surface is also indicated from the opposition effect seen in photometric phase curves (Deau, 2015).

CIRS radial scans measured at various observational geometries give a radial profile of the bolometric Bond albedo A_B (Morishima et al., 2010). The value of A_B is found to be correlated with the ring optical depth, τ: $A_\mathrm{B} = 0.1–0.4$ for the C ring ($\tau \sim 0.1$), $A_\mathrm{B} = 0.5$ for the A ring ($\tau \sim 0.5$), and $A_\mathrm{B} = 0.6–0.7$ for the B ring ($\tau \geqslant 0.7$). This correlation probably suggests that Saturn's rings have been continuously polluted by meteoroid bombardments and that pollution is more effective for optically thinner rings (Cuzzi and Estrada, 1998; Elliott and Esposito, 2011). The radial variation of A_B inside the A ring is found to be quite small (Morishima et al., 2010). This is consistent with the small radial variation of visual and near-infrared reflectances of the A ring (Porco et al., 2005; Hedman et al., 2013).

At the solar equinox in August 2009, Saturn's rings revealed the lowest temperatures ever observed; there was no temperature difference between the southern and northern faces (Spilker et al., 2013). At the equinox, as the Saturn flux is dominant, the ring temperature decreases with increasing saturnocentric distance. The equinox temperature is found to be relatively higher at optically thinner regions, because ring particles in thin rings can be heated by both the southern and northern hemispheres of Saturn. The observed equinox temperatures can be well reproduced by the models used in Spilker et al. (2013), except for the A ring. They applied a multi-particle-layer model developed by Morishima et al. (2009) to the equinox data of the A ring and found that the observed A ring temperatures are much higher than model predictions in which only the energy source at the equinox is assumed to be the thermal and solar-reflected fluxes from Saturn. The equinox temperature anomaly is particularly prominent in the middle A ring; almost all the radial scans taken at the equinox show a temperature peak around 129,000 km for the A ring.

In this paper, we examine two possibilities for the equinox temperature anomaly of the A ring. The first one is that the multi-particle-layer structure assumed in Morishima et al. (2009) is inappropriate for the A ring. Since the radial peak location of the equinox temperature coincides with the peak location of the amplitude of photometric azimuthal brightness asymmetry caused by self-gravity wakes (Dones et al., 1993; French et al., 2007), the discrepancy between the modeled and observed equinox temperatures may be due to wakes that are not taken into account in Morishima et al. (2009). In Morishima et al. (2014), we have developed a new thermal model in which wakes are represented by infinitely long elliptical cylinders, originally introduced by Hedman et al. (2007). This model can reproduce the observed azimuthal temperature modulation, which is found to be caused by the variation of the geometric filling factor seen from the Sun. In the present paper, we apply the wake model of Morishima et al. (2014) to the A ring data at the equinox. We also perform some additional parameter studies using the multi-particle-layer model of Morishima et al. (2009), because the entire parameter space has not been exhausted in Spilker et al. (2013).

The second possibility, for which we spend much more time than the first one, is incomplete cooling down of A ring particles at the equinox due to the effect of a seasonal thermal inertia. If the thermal inertia of the interior of a ring particle is high, the interior cools more slowly than the particle surface. The heat transport from the interior warms up the surface, which leads to a higher ring temperature than a model prediction without this seasonal effect. Therefore, if the equinox temperature anomaly is really due to the seasonal effect, we are able to give constraints on the seasonal thermal inertia, using seasonal temperature variation curves including the equinox data. The thermal skin depth associated with the seasonal effect is a few order of magnitude larger than the diurnal skin depth, and is comparable to the ring particle size. Thus, combining with the diurnal thermal inertia, it is possible to clarify how the fluffiness of ring particles changes with their depth. The seasonal thermal inertia can be constrained only if the particle size is larger than the seasonal thermal skin depth. Otherwise, the temperature of the entire particle down to its center quickly adjusts to the equilibrium temperature determined from external heat sources. Thus, either the particle size or the seasonal thermal inertia would be constrained.

In Section 2, we explain our methodology. In Section 3, we analyze the CIRS equinox data, using two sophisticated radiative transfer models which assume extremely different ring structures. We will show that the equinox temperatures for the A ring are much higher than the model estimates regardless of ring structure assumed in the models, as long as only the flux from Saturn is taken into account. In Section 4, we analyze seasonal temperature variation using all the existing CIRS data. We introduce a simple seasonal temperature model in which the thermal diffusion equation is

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