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The Dark Red Spot on KBO Haumea

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Abstract. Kuiper belt object 136108 Haumea is one of the most fascinating bodies in our solar system. Approximately $2000 \times 1600 \times 1000$ km in size, it is one of the largest Kuiper belt objects (KBOs) and an unusually elongated one for its size. The shape of Haumea is the result of rotational deformation due to its extremely short 3.9-hour rotation period. Unlike other 1000 km-scale KBOs which are coated in methane ice the surface of Haumea is covered in almost pure H_2O-ice. The bulk density of Haumea, estimated around 2.6 g cm^{-3}, suggests a more rocky interior composition, different from the H_2O-ice surface. Recently, Haumea has become the second KBO after Pluto to show observable signs of surface features. A region darker and redder than the average surface of Haumea has been identified, the composition and origin of which remain unknown. I discuss this recent finding and what it may tell us about Haumea.

Keywords. Kuiper Belt, techniques: photometric, infrared: solar system

1. Introduction

The Kuiper belt is currently the observational frontier of our solar system. Presumably the best kept remnants of the icy planetesimals that formed the outer planets, Kuiper belt objects (KBOs) have been the subjects of intense study in the past ~15 years. One intriguing KBO is 136108 Haumea (formerly 2003 EL_{61}). First famous for its super-fast rotation and elongated shape, Haumea went on to surprise us with a host of interesting properties. Haumea's spin frequency of one rotation every $\sim$ 3.9 hr is unparalleled for an object this large (Sheppard *et al.* 2008). Its shape is rotationally deformed into a $2000 \times 1600 \times 1000$ km triaxial ellipsoid (Rabinowitz *et al.* 2006) to balance gravitational and centripetal accelerations. To attain such a fast rotation, Haumea might have suffered a giant impact at the time when the Kuiper belt was massive enough to render such events likely. Infrared spectroscopy has revealed a surface covered in almost pure H_2O ice (Trujillo *et al.* 2007) which gives Haumea an optically blue colour (Tegler *et al.* 2007). The surfaces of the remaining Pluto-sized KBOs (Eris, Pluto and Makemake) are covered in CH_4 ice instead, granting them the tag 'Methanoids'. Two satellites were discovered in orbit around Haumea (Brown *et al.* 2006), the largest of which is also coated in even purer H_2O ice (Barkume *et al.* 2006). The two satellites have nearly coplanar orbits with fast-evolving, complex dynamics due mainly to tidal effects from the primary (Ragozzine & Brown 2009). Haumea's bulk density, derived assuming it is near hydrostatic equilibrium, is $\rho \sim 2.6$ g cm^{-3} (Lacerda & Jewitt 2007). The surface material has density $\rho \sim 1$ in the same units implying that the interior must be differentiated and Haumea must have more rock-rich core. A number of KBOs showing signs of H_2O ice in their surface spectra all lie close to Haumea in orbital space (Schaller & Brown 2008); this, plus the unusually fast spin, the differentiated inner structure and the two small satellites also covered in H_2O ice, all have been taken as evidence that Haumea is the largest remnant of a massive collision that occured > 1 Gyr ago (Ragozzine & Brown 2007, Brown *et al.* 2007). However, several potential members of the collisional family have been eliminated based on infrared photometry (Snodgrass *et al.*, poster at this meeting).

2. The Dark Red Spot (DRS) on Haumea

We observed Haumea in mid-2007 using the University of Hawaii 2.2m telescope with the goal of measuring its lightcurve in two bands, B and R (Fig. 1a). Our high-quality photometry (Lacerda *et al.* 2008) shows two important features:

(a) The lightcurve is not symmetric as would be expected from a uniform ellipsoidal body. There is a clear asymmetry between the two sets of minima and maxima indicating the presence of a dark region on the surface (Fig. 1a). A model lightcurve generated by placing a dark spot on the equator of Haumea, visible at both minimum and maximum cross-section (Fig. 1b), successfully fits the data.

(b) Upon aligning the B and R lightcurve data we verify that the B points lie consistently below the R points precisely at the location of the dark spot. In other words, the dark spot is also redder than the average surface.

In the rest of the paper we use DRS to refer to the dark red spot. In our model (Fig. 1) the size and relative darkness of the DRS are degenerate: the spot may be as small as a few percent of the projected cross-section of Haumea and be about 20% as reflective as the rest of the surface, or it may be as large as to take a full hemisphere of Haumea being then only 5% less reflective than elsewhere. The same degeneracy applies to colour vs. spot size. However, assuming the DRS colour is within the range of values typically found in the solar system, $1.0 \lesssim B - R$ (mag) $\lesssim 2.5$, then when directly facing the observer the spot must take between 20% and 60% of the projected cross-section of Haumea, and have an albedo between 55% and 65%. This combination of colour and albedo is consistent with, e.g. Eris, Makemake and the bright regions on Pluto and on Saturn's satellite Iapetus; it is inconsistent with Pluto's darker regions, with Pluto's satellite Charon, with Saturn's irregular satellite Phoebe and with Centaurs Chiron and Pholus.

3. The DRS in the infrared

Prompted by the fact that Haumea is covered in H_2O ice, we set out to investigate how the properties of the ice changed close the DRS region by monitoring the infrared

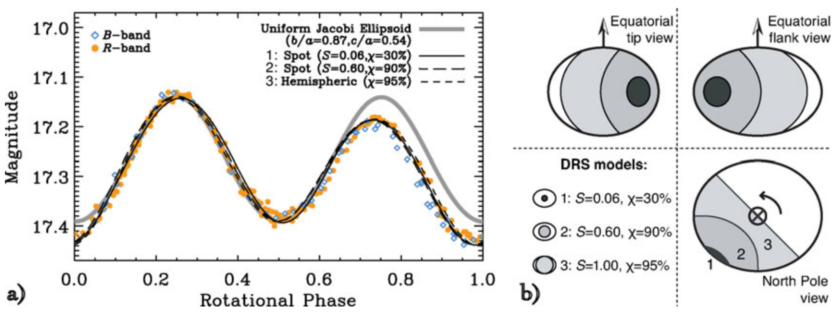

Figure 1. a) Lightcurve of Haumea in two filters. Both B and R data were taken over 3 nights to ensure repeatability. The effect of the dark red spot is apparent at rotational phases $0.7 \lesssim \phi \lesssim 1.0$: the maximum and minimum that bracket that region appear darker and the B-band flux is consistently lower than the R-band flux indicating the spot is redder than elsewhere. We measure a lightcurve period $P = 3.9155 \pm 0.0001$ hours and a photometric range $\Delta m = 0.29 \pm 0.02$ mag. The rotationally averaged colour is $B - R = 0.972 \pm 0.017$ mag. Best fit Jacobi ellipsoid models are overplotted: a thick solid grey line shows how the uniform surface model fails to fit the dark red spot region, and thinner lines show that a small ($S << 1$) and very dark ($\chi << 100\%$) spot or a large ($S \sim 1$) and not very dark ($\chi \sim 100\%$) spot fit the data equally well. **b)** Cartoon representation of the three spot models considered in a) showing the location of the spot on the surface of Haumea.

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H_2O-ice absorption band at 1.5 μm (Fig. 2). We collected two sets of data: time-resolved, quasi-simultaneous broadband J (to probe the continuum) and medium band CH_4s (to probe the 1.5 μm) data using UKIRT, and a similar dataset at the Subaru telescope this time using broadband filters J and H. Both telescopes are located atop Mauna Kea.

Neither of the filters CH_4s or H fully probe the 1.5 μm band, and both are affected by a narrower band at 1.65 μm which, if present, indicates that the ice is mostly crystalline (Merlin *et al.* 2007). Our UKIRT measurements indicate that the CH_4s/J flux ratio decreases by a few percent close to the DRS, while our Subaru measurement show that the H/J flux ratio increases also by a few percent. This apparent contradiction can be explained if the DRS is richer in crystalline H_2O-ice than the rest of the surface. That would change the shape of the 1.5 μm and 1.65 μm bands and cause exactly what is observed (see Fig. 2a). Fraser & Brown (2009) report *HST* NICMOS observations of Haumea using the broadband filters F110W and F160W centered respectively at 1.1 μm and 1.6 μm. They find that the F160W/F110W flux ratio decreases at the DRS, consistent with our UKIRT observations. Infrared spectra obtained at 4-m-class telescopes show no rotational variations, likely due to lack of sensitivity (Pinilla-Alonso *et al.* 2009).

4. The DRS 4-band spectrum

Using the time-resolved BR data from the UH 2.2 m and JH data from Subaru we constructed 4-band spectra of Haumea as it rotates. We did this by interpolating each of the four lightcurves and measuring the relative differences between the bands. The result is shown in Fig. 2b where we plot 3 spectra away from the DRS ($\phi = 0.3, 0.4, 0.6$) and 3 spectra close to the DRS ($\phi = 0.7, 0.8, 0.9$). The Figure shows that the DRS material is a more efficient B absorber than the rest of Haumea, hence the redder $B-R$ colour, and that it is redder in visible-to-infrared colour. In §3 we saw that the DRS displays bluer or redder behaviour in the JH wavelength range depending on exactly which filter bandpasses are used.

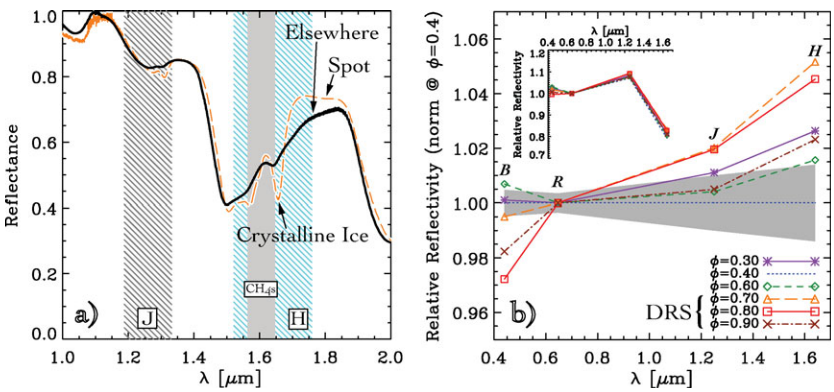

Figure 2. a) Near-infrared synthetic spectra of H_2O-ice. The orange dashed line shows a spectrum of crystalline ice (indicated by the 1.65 μm feature) while the solid black line corresponds to ice with a lower degree of crystallinity. **b)** Time-resolved 4-band spectrum of Haumea [adapted from Lacerda (2009)]. Each line is a spectrum at a given rotational phase. At rotational phases when the DRS faces the observer ($0.7 \lesssim \phi \lesssim 1.0$) the B band is depressed and the H band is enhanced. Spectra at each rotational phase are plotted relative to R band and all rotational phases have been normalised by $\phi = 0.4$. Inset shows spectra before normalisation at $\phi = 0.4$.

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5. Interpretation

It is very unlikely that the dark spot is a topographical feature such as a mountain or valley as that would produce an achromatic change in brightness. Instead, the spot region exhibits slight but persistent visible and infrared colour properties that distinguish it from the rest of Haumea's surface. No atmosphere has been detected on Haumea rendering an explanation based on irregular condensation of gases on the surface unlikely. The fact that the DRS absorbs B-band light more efficiently could indicate the presence of hydrated minerals (Jewitt *et al.* 2007). Alternatively the redder tint could be due to the presence of irradiated organic materials which would also explain the blue behaviour observed in some infrared bandpasses (Fraser & Brown 2009). If confirmed, the higher degree of ice crystallinity at the DRS could signal a recent temperature rise.

6. Speculation

The DRS could be a region where material from Haumea's interior is trickling out. The high bulk density of Haumea indicates the presence of a more mineral-rich core. If warmer, deep-lying material would find its way to the surface it would appear darker and presumably redder than H_2O ice. The slight increase in temperature and the presence of H_2O are useful ingredients for mineral hydration and H_2O-ice crystallinization.

The DRS could also be the site of a recent impact of a $\sim 1-10$ km KBO onto Haumea. Small KBOs are dark and most are believed to be covered in red, irradiated organic mantles. The collision would locally raise the temperature, thereby accelerating the transition from amorphous-to-crystalline H_2O ice, and the impactor material would probably leave a visible trace on the surface.

The DRS could also be due to something completely different. Time-resolved spectroscopy of Haumea using $8-10$ m telescopes should help determine the composition of the DRS and help solve the mystery of its origin.

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