Infrared Observations of Distant Asteroids.

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Abstract. We present new infrared spectra of the unusual minor planet 5145 Pholus which shows a featureless J band spectrum and does not confirm the 1.72μm feature weakly detected by Luu, Jewitt and Cloutis (1994). Revised VJHK colours of Pholus from 1992 are presented which confirm the extreme redness of the visual-IR colours. A new detection of 5145 Pholus at 20μm is combined with earlier data and suggests that the diameter of the object is 185 $\pm$ 16 km. JHK photometry of 1993HA$_2$, and an upper limit for the J magnitude of 1993FW, is presented and the VJHK colours of all three objects are discussed.

1. Introduction

Several new distant solar system objects have been discovered in the last few years. These include the Centaur objects, 5145 Pholus and 1993HA$_2$, and a number of trans-Neptunian objects. Since small solar system objects often show trends of increased reddening with heliocentric distance the infrared region may offer a number of clues in determining the relationships of the various types of objects. In this paper we present new data on three of them.

2. Observations and Analysis

2.1. 5145 Pholus

Minor Planet 5145 Pholus was discovered in 1992 (Scotti 1992) and quickly found to be extremely red in the visual region (Mueller et al (1992), Fink et al (1992), Binzel (1992)). Davies and Sykes (1992) reported JHK colours and combined these with a V magnitude extrapolated from non-simultaneous visual data to estimate visual to infrared colours of V-J=2.46 and V-K= 2.87. Buie and Bus (1992) determined several important physical parameters for the object including its lightcurve, absolute magnitude and the dependence of V-R colour with phase. Pholus was found to have an unusual infrared spectrum (Davies et al 1993b) which showed deep absorption features in the K band. Cruikshank et al (1993) suggested an identification of these features with members of the class of organic solids known as asphaltites and Wilson et al (1994) described a comprehensive attempt to match the spectra to a mixture of organic solids and ices. Luu, Jewitt and Cloutis (1994) published further IR spectroscopy and confirmed the presence of deep features in K band. They also reported a weak feature at 1.72μm in the otherwise featureless H spectrum. Howell et al (1992) estimated the diameter to be 140 km with an albedo of 0.08 and Davies et al (1993a) reported 20μm detections which suggested a minimum diameter of 189 km and a visual albedo 0.044.

We first consider the VJHK colours. Using the lightcurve of Buie and Bus (1992) it is now possible to improve on the estimate of the V magnitude during the 1992 JHK photometry. From this it is apparent that the JHK photometry was taken at phases of 0.76 and 0.29 which are both close to maximum light. It is also possible to use the H and G parameters presented by Buie and Bus to make an improved estimate of the visual magnitude of Pholus at the times of the JHK observations and this gives V magnitudes of 17.25 and 17.28 respectively. By co-incidence the two sources of error in the originally quoted visual to infrared colours (light-curve effects and assumed V magnitude) almost cancel and result in colours which have similar values to those reported in 1992, but with somewhat lower uncertainties. The revised values are included in Table 1.

On 12 May 1994 5145 Pholus was observed with the UKIRT bolometer UKT8 and found to have a 20μm magnitude of Q = 4.6 $\pm$ 0.26. S. F. Green (private communication) used a standard thermal model with with G=0.16, beaming parameter = 0.756, emissivity=0.9 and IR phase coefficient=0.01 mag/deg to compare this with the data reported by Davies et al (1993a). From the 1993 data he determined a visual albedo of 0.040 $\pm$ 0.02 and diameter 191 $\pm$ 25 km in good agreement with that of Davies et al 1993a. For the 1994 data he deduced a visual albedo of 0.046 $\pm$ 0.02 and diameter 178 $\pm$ 20km. The errors were assessed by taking Q error as stated, V error as 0.15 mag (which included 0.11 mag for H error, 0.03 mag resulting from G error, 0.1 mag for lightcurve.). These results are internally consistent and imply that Pholus is both larger and darker than the preliminary result by Howell et al (1992).

As noted above Pholus was found to have an unusual infrared spectrum (Davies et al 1993b) which has been interpreted as arising in organic molecules. Luu, Jewitt and Cloutis (1994) published further IR spectroscopy and confirmed the presence of deep features in the K band. They also reported a weak absorption at 1.72μm in the otherwise featureless H spectrum. Since the detection of features in the near infrared may be crucial to identifying the material on the surface of Pholus we re-observed the object in April 1994. Spectra from 1.14 to 1.36μm (J band) were taken on 1994 April 19 and 1994 April 20. In order to determine the reflectence spectrum of the asteroid these spectra were ratioed with a nearby G0V star (BS4027) observed at a similar time and airmass. This is less rigourous than ratioing by a solar analogue star but since the IR spectrum of G stars is featureless at the resolutions used we consider it a reasonable approximation. When possible, data ratioed by a G star was compared with the same data ratioed by the solar analogue Hyades 64 and the resulting spectra do not show significant differences. The 1994 J band spectra of Pholus (figure 1) does not show any significant spectral features.

Spectra from 1.46 to 1.85μm were taken on 1994 April 19 and 1994 April 24 in an attempt to verfiy the existence of the 1.72μm feature reported by Luu, Jewitt and Cloutis (1994). These spectra were treated similarly to the J band data, ie they were ratioed by a nearby G star (BS4027) to determine reflectivity. Our examination of these new spectra do not show any clear evidence for the feature reported by Luu, Jewitt and Cloutis.

Noting that the feature is known to be weak we attempted to estimate the significance of this result as follows. The data for April 19 and April 24 were normalised and co-added to improve the signal to noise. (figure 2) The mean value and standard deviation over 7 pixels was calculated for regions 0.02μm wide centred at at 1.66, 1.68, 1.72, 1.74 and 1.76μm. The expected value at 1.72μm was then interpolated between the closest values on either side. The difference between the actual value and interpolated values was then compared. Since the feature might be broad, this procedure was repeated using the data at 1.66 and 1.766μm to determine the expected flux at 1.72μm. Both calculations gave the same result, which is that our 1994 data is consistent with there being no feature at 1.72μm.

Luu, Jewitt and Cloutis did not estimate the depth of the feature beyond saying that it was weak. We have examined their spectrum and deduce that the depth of the feature is about 2.5 percent of the continuum. If this is correct then the expected depth of the feature is 1.4 times the 1 sigma expected error of our 1994 data. For comparison we estimate that the depth of the feature in the Luu, Jewitt and Cloutis data is 1.8 times greater than the error in their data.

Interpretation of this result is difficult since both the detection of the feature in 1993 and the non-detection in 1994 rest on data in which the signal to noise ratio is close to the expected depth of the feature. While it might be possible to explain the apparent change in terms of rotation of the asteroid we note that Buie and Bus (1992) reported that the V-R colour was almost constant over the entire rotation period which makes it unlikely that there are large differences in the surface composition across the object. The uncertainty in the lightcurve, and lack of any information about precession, means it is not possible to extrapolate between observations over 1 year apart in order to determine if the two datasets were taken at different phases or orientations. It is clear that a resolution to this question may have to wait until even higher signal to noise spectra of Pholus can be obtained. This may be possible in 1995 when the UKIRT CGS4 spectrometer is expected to re-enter service with a 256 square array giving better spectral resolution and higher signal to noise ratio.

Note added in press. Cruikshank et al (in press) will present new Pholus data taken with the upgraded CGS4 spectrometer in 1995.

2.2. 1993HA$_2$

1993HA$_2$ was discovered on 26 April 1993 by the Spacewatch asteroid search project (Rabinowitz 1993). The object has a perihelion beyond Saturn and aphelion inside Pluto (a=24.87, e=0.5235). No cometary activity has been reported and the orbital similarity to 5145 Pholus encouraged us to obtain near infrared colours of 1993HA$_2$ for comparison.

1993HA$_2$ was observed using the infrared camera IRCAM in its 0.62 arc sec/pixel mode on the UK Infrared Telescope (UKIRT) during July 1993. The object was not visible in the telescope finder so pointing was done by offsetting from a nearby star. The identification of the asteroid was confirmed by noting its correct movement from night to night relative to faint background stars in the IRCAM images. On each night, images were taken in the J,H and K filters.

For each filter an observation comprised a mosaic of five separate frames, offset slightly from each other to minimise the effect of bad pixels. After subtracting an appropriate dark frame from the object frames, each set of five frames were median filtered to produce a flat field which was then subtracted from each frame. The resulting frames were co-added with appropriate offsets and deglitched to produce the final image. Each final image has a total exposure time of 900s. Software aperture photometry was performed on these images and calibrated relative to images of standard stars taken at similar airmasses at around the time of the asteroid observation. The final errors quoted combine internal errors in the images with uncertainties in photometric calibration.

The object was re-observed in April and July 1994 using the upgraded UKIRT infrared camera IRCAM3. The camera, which has a 256 square InSb array has a plate scale of 0.286 arc sec/pixel and a field of view of 73.2 arc sec. Each observation comprised mosaics of nine 20 second exposures with the first centred on the expected position of the object and the remainder jittered by $\pm$ 8 arc seconds in RA and Dec. Data reduction was similar to that for the earlier IRCAM data.

Since no lightcurve for 1993HA$_2$ has been reported, intepretation of this data in terms of visual to infrared colours is somewhat uncertain. The J,H and K magnitudes for April 1993 were averaged to produce. J=18.45 $\pm$ 0.1, H=18.09 $\pm$ 0.15 and K=18.19 $\pm$ 0.17. The infrared colours are then J-H = 0.36 $\pm$ 0.18 and H-K = -0.10 $\pm$0.23. Using an assumed absolute V magnitude of H=9.5, and ignoring any possible lightcurve effects, the mean V magnitude around the time of the observations is expected to have been V= 20.6 which implies a V-J of 2.15 $\pm$0.4 where an error in the estimated V magnitude of 0.3 has been allowed. On the same basis the April 1994 data imply an estimated V magnitude of 20.28 and V-J of 2.23 $\pm$0.3 and V-K of 2.42 $\pm$0.4. The July 1994 data, assuming V=20.7, gives V-J=2.31 and V-K=2.35 with similar errors to the April data. These data are formally consistent with the 1993 data and averaging all five data points gives V-J of 2.20 $\pm$ 0.4 and V-K = 2.4 $\pm$ 0.4. All of these data are presented in Table 1.

However, although the colours are consistent between 1993 and 1994, the April 1994 magnitudes differ considerably from the remainder of the data. Since the April 1994 observations were done close to zero phase then a phase effect of Delta V = 0.3 has been assumed. The different Sun-Asteroid-Earth distances contribute another 0.05 magnitudes, and this is sufficient to bring the data into agreement without the need to invoke the (unknown) lightcurve effects.

2.3. 1993FW

This object was discovered in March 1993 (Luu and Jewitt 1993), observed again on May 17.05 1993 with V magnitude of 23 by Hainaut (1993) and recovered in early 1994. According to Marsden (1994) the object has a semi-major axis of 43.908AU and an eccentricity of 0.04058. At discovery the Mould R mag-

Table 1. Summary of JHK data.

5145 PHOLUS

UT Date	Phase	V(est)	J	H	K	J-K	V-J	V-K
1992 Mar 15.399	5.6	17.25	14.78±0.02	14.27±0.02	14.32± 0.02	0.46	2.47	2.93
1992 Mar 17.281	5.7	17.28	14.69±0.02	14.31±0.03	14.33±0.00	0.36	2.59	2.95

1993HA$_2$

UT Date	Phase	V(est)	J	H	K	J-K	V-J	V-K
1993 Jul 3.292	4.6	20.6	18.43±0.15	17.89±0.25	18.45±0.3	-0.02	2.17	2.15
1993 Jul 4.358	4.6	20.6	18.33±0.15	18.00±0.25	17.88±0.3	0.45	2.27	2.72
1993 Jul 5.265	4.6	20.6	18.58±0.15	18.39±0.25	18.24±0.3	0.34	2.02	2.36
1994 Apr 27.081	0.8	20.28	18.05±0.13	-	17.78±0.3	0.27	2.23	2.50
1994 Jul 14.335	4.4	20.70	18.39±0.13	18.16±0.25	18.35±0.3	0.04	2.31	2.35

nitude was estimated as 22.8 ±0.1 and the V-R colour as 0.4 ±0.1. The 1994 observations reported V=23.5 on Jan 11.36 and R=23.5 on Jan 14.36.

A search for 1993FW on April 27.35 with IRCAM3 on UKIRT did not detect the object. The observing techinque of nine position, jittered mosaics was similar to that of the IRCAM3 observations of 1993HA$_2$ described above. After each mosiac the telescope was repointed to the expected position of the asteroid and another mosaic was taken. Over a period of two hours a total of eight such mosaics (total integration time about 1280 seconds due to occasional lost frames and overheads) were taken and the results co-added to produce a final image. There is no obvious detection of 1993FW in this image and in a two arc second software aperture the deduced 5 sigma upper limit at J is 22.0. Combining this with an estimated V magnitude of 23.3 implies a V-J colour of less than 1.5.

3. Discussion

Table 2 Presents a summary of the IR data described here together with V-R data from the literature.

Table 2. Visual to IR Colours of Outer Solar System objects.

Object	V (Estimated at time of observation)	V-R	V-J	V-K	Note
Pholus	17.2	0.81	2.53 ± 0.06	2.94 ± 0.06	V-R from Buie and Bus (1992)
1993HA$_2$	20.6	-	2.2 ± 0.4	2.4 ±0.4	
1993FW	23	0.4	<1.5	-	V-R from Luu (1993)

All of the visual to infrared colours reported here depend on the accuracy with which the V magnitude can be extrapolated to the time of the infrared observations using the published values of H. Although this must add some additional uncertainty to the derived colours the data appears to show that the few distant asteroids observed so far exhibit a range of visual to infrared colours. The colours of $1993HA_2$, although redder than most other solar system objects, appear to be less red than those of the dynamically similar object 5145 Pholus. Comparison with the VJHK colours of other remote solar system bodies (eg Fig 3 based on data from Tokunaga 1996) suggest that the V-J colour of $1993HA_2$ falls between those of the quiescent nucleus of comet P/Schwassmann-Wachmann-1 and those of 5145 Pholus. However, the visual to IR colours of all three of these objects are far more extreme than those of the outer solar system object 2060 Chiron, (diameter 182km (Campins et al 1994)) which has been observed to have developed cometary activity in recent years.

Interestingly the visual to IR colour of 1993FW appears to be less red than both 5145 Pholus and $1993HA_2$ and only marginally consistent with the V-J colour of comet P/Schwassmann-Wachmann-1. This implies that the trend of extreme reddening with heliocentric distance cannot be assumed to hold true for all distant asteroids. It is not yet clear how these colours are related to the actions of solar radiation and occasional cometary activity and, until better visual to IR colours can be obtained for a larger sample of these very distant objects it may be unwise to assume that Pholus can be used as a prototype for the Kuiper Belt objects. In view of the small number of objects observed, and the relatively large uncertainties, further infrared observations, combined where possible with simultaneous visual photometry, of distant asteroids are urgently required.

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Figure captions.

Figure 1. The 1.15 to 1.35 micron spectrum of Pholus on 19 April 1994. The spectrum of the object has been divided by that of the G0V star BS4027 to produce a reflectance spectrum.

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Figure 2. A 1.44 to 1.85 micron spectrum of Pholus produced by averaging data from 19 and 24 April 1994. On each night the spectrum of the object was divided by that of the G0V star BS4027 to produce a reflectance spectrum before averaging the data.

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Figure 3. The V-J,J-K colours of the objects discussed here plotted with the colours of some icy outer solar system bodies. Solar colours have not been removed from this data. J=Jupiter satellite,S=Saturn satellite, U=Uranus satellite,Tr=Triton,P&C=Pluto & Charon. T denotes trailing hemishere, L denotes leading hemisphere