Measurement of the Near Infrared Opposition Surge of Triton Near True Opposition
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ABSTRACT
We present Near Infrared (J, H, Ks-band) photometry of Triton obtained around the opposition of August 13, 2007 UT. Observations were conducted using a HAWAII-1 infrared camera operating at the University of Virginia’s Fan Mountain Observatory’s 31-inch reflector. With Neptune near a node crossing, Triton reached solar phase angles as small as 0.009 degrees. Given a heliocentric distance of 30AU, the Sun’s angular radius was only 0.008 degrees. The observing campaign took place in two part; one around opposition and the other about a month later in order to characterize the light curve of Triton at these wavelengths while the phase angle was slowly changing. The observations successfully characterize the angular width, amplitude, and wavelength dependence of the Near Infrared opposition surge of Triton and provide evidence for a significant contribution from the coherent backscatter effect.

SPATIAL PICTURE
Triton is a Kuiper Belt Object (KBO) captured in orbit around Neptune.

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EARLE
Shadow Hiding is entirely a geometric phenomenon. This means that for phase angles less than 0.010 degrees, the object being observed looks brighter, or rather has a lower magnitude than would otherwise. Because shadow hiding is directly correlated to the angle of observation, this effect dominates the phase angles closest to zero. Shadow hiding works only when the particles on the observed surface are larger than the wavelength of light at which the observation is made (in our case lambda J, H, and Ks). In our data, we received data for phase angles of that range because a zero phase angle would only have been observable during our daytime. The next effect has more to do with the Triton surface than the phase angle, though low phase angles amplify it. For icy objects like Triton that have high albedos, or are very reflective, the Shadow Hiding phenomenon predicts that the opposition surge observed to be small. This makes sense because there is a higher fraction of light scattered between regolith particles that fill in shadows. That is to say that for icy satellites, a surge comes predominately not from geometry, but rather a regolith surface or even something else, coherent backscattering. In addition, the brightness of Triton in opposition as it relates to shadow hiding, is only applicable for singly scattered light.

Regolith Surface

Triton is a captured satellite and not a moon of (with the connotation of moon being derived from) Neptune. Its polar alignment does not match that which is common to the ecliptic disk. We are looking at its south pole; a region dominated by methane geysers and ice. Light shining on this regolith type surface at low phase angles will cause much more light to be reflected back to the observer than otherwise noted. It is important to note that the reflection from the ice in our direction is due to frozen methane and nitrogen molecules (a roughness somewhere between a microscopic and macroscopic scale relative to the near infrared bands we used in observation; a grain sized at a micrometer). Triton’s albedo then is much higher at this southern cap. Hapke, Nelson, and Horn describe in their paper on Selected Particulate Materials that “the geometric optics effects are the product of singly and multiply scattered radiation reflected from the surfaces of the regolith particles, combined with radiation which has undergone various combinations of transmission through one or more regolith grains followed by one or more scatterings from other particles.” Basically, the radiation they refer to is electromagnetic or light, and as it bounces around on the surface of Triton, and is then reflected back across the angle of incidence towards its source. It just so happens that in our case, we are with the source in direction so too see this increase in brightness. Because an apparent issue of uniformity obviously arises when dealing with ice that may or may not be evenly distributed, and a thin Triton atmosphere generated by the methane released, we created a light curve over the area of observation to determine how to adjust our results to account for the variance. From our data over the periodic longitudes of observation, no such adjustment was deemed necessary. The final and most controversial effect observed is unique to our study with specific reference to the wavelengths of observation.

Coherent Backscattering

The Coherent Backscattering of light is a phenomenon in which light constructively interferes with itself after reversing direction when contact is made with an object. The observed surface exhibits a nonlinear increase in intensity of reflected electromagnetic radiation when observed at such small phase angles. The reasons behind the multiple
scattering effect are not fully understood, but what has been theorized deals directly with our case study. For larger wavelengths, the effect should be observed in relatively higher phase angles. Because our observation was outside the optical range, we hoped to see the brightening effect for higher phase angles.

TRITON OBSERVED

CCD Photometry

When taking photometry of an object, one can either choose to employ relative or absolute photometry. Relative photometry concerns itself with measuring the magnitude or relative brightness of stars and other celestial bodies with respect to one another, and less with what the absolute flux or light received from that object. Therefore, in this Triton survey, we measure brightness differences but not necessarily the magnitude of the body itself. However, because there are standard stars in our field of observation, we are able to incorporate elements of absolute photometry. A standard star is just a source that has been measured many times in photometric conditions, and has an either fairly constant magnitude or predictable variability. For absolute magnitude to be effective, more factors must be accounted for to insure the reliability of our final result. One such factor deals with differing air masses over several observations. As stars and other object set, they appear to head for our Earth’s horizon, and because we are looking through an atmosphere at an angle, we have more “stuff” to look through that could potentially skew our data. For this reason, Triton’s photometry comes from air masses close to one, or when Triton is directly overhead. Because all the stars in our field of view are seen through the same air mass despite the frame, we are able to code for strictly their relative brightness, and then find the additive factor by which a standard star is displaced, and add that factor to our Tritonian magnitude to receive its absolute magnitude. The Fan Mountain 31-inch telescope and infrared camera served as the instruments for this observation. The camera was designed and fabricated by graduate students Srikrishna Kanneganti and Chan Park. The optics re-image the sky onto a 1024x1024 HgCdTe HAWAII-1 array with a pixel scale of 0.51”/pixel providing an 8.5’x8.5’ field of view. Fan Mountain Observatory is located at a dark site 15 miles south of Charlottesville, VA. Ten minutes of on-source integration time yields 10-sigma limiting magnitudes of 18, 17, and 16 at J, H, and Ks-bands respectively. For comparison, Triton is slightly brighter than those limiting magnitudes in these bands.

Optical Properties of Ices For Infrared

The best range of wavelength to study an icy surface depends entirely upon the nature of the research. Because we are more concerned with the effect coherent backscattering is having on the surface, we observe in the near infrared J (1.26 micrometers), H (1.60 micrometers), and Ks (2.22 micrometers) bands. Based on spectra in these wavelengths for icy surfaces, we are able to determine and verify the molecular properties of a surface. The width of our surge tells us something further about the surface, namely the microphysical spacing of the grains. The width of the surge is directly related to the wavelength of opposition over particle size.


TRITON OBSERVED

Results
Below is a graph representing the magnitude of Triton at J, H, and Ks bands as a function of solar phase angle (phase angle on the x axis and magnitude on the y axis).

![Graph showing magnitude vs phase angle for Triton at J, H, and Ks bands.]

**FIGURE B**

A significant wavelength-dependent opposition surge is evident at the smallest phase angles (<0.1 degree). The width (Full Width Half Max or FWHM) of the surge increases with wavelength, consistent with the trend predicted by coherent backscatter theory. A particulate surface produces an opposition as the result of at least two distinct phenomena: shadow hiding and coherent backscatter as described earlier on. The shadow hiding surge in our results is manifested over a broad range of phase angle (0-20 degrees) when particles hide their own shadows as phase angles decrease to zero; it is not wavelength dependent, nor is it evident in the data presented here. However, the coherent backscatter opposition effect, a constructive interference phenomenon is manifested over a much narrower range of phase angles (0-2 degrees). According to theory, the angular width (FWHM) of the surge should increase with wavelength. This trend is evident in the data between solar phase angles of 0 and 0.2 degrees.

Representative J-band (1.25um), and Ks-band (2.16um) 30 second exposures consistently showed Triton and Neptune as well as several companion stars within the field of view.

**FIGURE C**

// Triton is the smaller object located on top. Neptune is the bright object at the frame’s center. //
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FIGURE D

Ks-band

// Triton is leftmost and Neptune rightmost.

Neptune is fainter than Triton at Ks due to methane and molecular hydrogen absorption in Neptune’s atmosphere. Each night approximately twenty such exposures were obtained at each J, H, and Ks-bands and the mean difference between Triton and the 2MASS magnitude of a selected companion star of comparable brightness was computed. The source position was moved to a different focal plane location for each exposure to mitigate systematic calibration errors. Internal flux/magnitude uncertainties are <1% (0.01 magnitude). Precision of the final measurements is limited to 2% (0.02 magnitude) by the uncertainty in the flux of the 2MASS reference star. This uncertainty could be be improved in the future with further analysis using all of the reference stars in the field. However, because some of these companion stars saturate the CCD camera, they can not be utilized because we are not getting their full value from the CCD (the CCD cell is topped out).

The following light curve of Triton J, H, and Ks-bands, are shown as a function of longitude with the magnitude again along the y-axis and this time, the longitude observed along the x-axis. The plot comprises only the points on the above chart at phase angles >0.5 degrees. Overall, the amplitude of the light curve is small. The leading hemisphere is approximately 0.05 magnitudes brighter than the trailing hemisphere in the three bands studied here. Because of this small amplitude,