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Models of the SL-9 collision-generated hazes

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Abstract. From subarcsec-seeing infrared images and spectra in the K and H bands, we present reflectivities and limb-darkening results for two of the hazy regions generated during the SL-9 collision. These highly reflective impact areas at infrared methane wavelengths have been studied in terms of multiple scattering radiative models. The results for both the H and D/G impact remnants show that a considerable amount of particles have been injected in Jovian stratospheric levels from ~1 mbar to the upper level of the assumed Jovian tropospheric NH_3 ice haze (at ~350 mbar). Our models suggest a concentration of small particles, with mean radius of 0.15 μm for a real refractive index of 1.7. The imaginary refractive indices are in the range 1×10^{-4} to 1×10^{-3}. For the H impact region, absorption at 2.0 μm is enhanced compared to unperturbed regions at the same scattering geometry. This enhancement is not observed in the older D/G complex.

1. Introduction

As was shown in the spatially resolved measurements by *Moreno et al.* [1993], the reflectivity at the deep 1.7 and 2.3 μm methane bands is extremely low at most regions of Jupiter and particularly low at -50° latitude. This encouraged us to observe the SL-9 collision with Jupiter at these wavelengths, since small amounts of particles released by an impactor would scatter some light and greatly affect the reflectivity. In addition, we would be able to detect thermal emission if the heating reached sufficiently high atmospheric levels where opacity due to overlying methane is low enough so that thermal emission could escape.

This strategy proved fruitful, as was demonstrated by the detection of the first impact (IAU Circ. No. 6022). The long times that the impact areas were visible travelling across the Jovian disk, their high reflectivity compared to nearby regions, and the absence of strong limb darkening first suggested that the impacts generated clouds or hazes at very high levels. Nevertheless, these data were not interpreted in detail. Such an interpretation is accomplished to a certain extent here, where we deal only with scattering and absorption of sunlight within the "remnant" or "scar".

2. Observations and reductions

The images and spectra used here are part of a set of observations carried out at the f/10 Cassegrain focus of the 3.5-m telescope at Calar Alto Observatory (Spain) on the night 18/19 July 1994. We used the MAGIC detector [*Herbst and Rayner*, 1994]. The filters employed were centered at 1.50, 1.58, 1.7 and 2.3 μm, with bandpasses of 0.05, 0.01, 0.05 and 0.2 μm, respectively. The spectra covered the ranges 1.50 - 1.80 μm and 1.96 - 2.40 μm.

All the frames were sky-subtracted and flatfielded. Bad pixels were removed by interpolation. The image counts were then translated into reflectivities (I/F) by means of observations of the Solar analog 16 Cyg B for spectroscopy and by means of BS 5868 (a G-type star) for the imaging data. The calibration was carried out using their magnitudes in V and assuming m_V=-26.75 for the Sun [*Neckel*, 1986].

The geometric reductions consisted in the determination of planetographic coordinates and scattering angles (μ, μ_0, and $\Delta\Phi$) at the brightest pixels of the impact sites in the images. By comparing our measurements of Ganymede's albedo with other published data we estimate a 20 % uncertainty in our I/F at 1.7 and 2.3 μm. The bidimensional Jovian spectra were obtained

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with a 0.64 arcsec-wide slit aligned in East-West direction along a Jovian parallel at the impact latitude. They were collapsed by summing all the counts from a 3-arcsec region on the H and D/G scars. The resolving power of the experimental set up is estimated to be 360 [*Herbst et al.*, this issue]. The wavelength calibration was performed by using the OH airglow sky emissions and the estimated wavelength uncertainty is ±0.003 μm. In order to correct for telluric absorptions we obtained spectra of the solar analog 16 Cyg B at the same resolution. The narrow slit caused a stellar flux loss of 57 % as measured from the star profiles in the spatial direction of the bidimensional spectra, however, we can not prove that the star was exactly centered in the slit during the whole integration. Therefore, we estimate a large fractional error in the absolute calibration, which may be as high as 50%.

3. Observational results and models

The scatterers present in most of the impact areas formed dark clouds at continuum UV and visible wavelengths. However, we did not find a noticeable darkening of the impact regions at the 1.58 μm continuum. Only after deconvolution is applied to our images (see figure 1) can we barely see a dark dot. This suggested either that the dust particles had much smaller radii than the wavelength, thus causing much less extinction than in the visible, or that the particle absorption cross section strongly decreased toward the IR, or both. The observed reflectivities at the 4 filters of this study (for two different geometries) are presented in fig. 2. In fig. 3 we present the spectroscopic results.

The aerosol model is based on that proposed by *Moreno et al.* (this issue), in their interpretation of the H-site debris from 3600 to 9500 Å observations. These authors employed a distribution of spherical particles and computed reflectivities by using Mie theory in combination with a discrete ordinates method [*Stamnes et al.*, 1988]. Following *Moreno et al.*, the particles should be distributed between 1 and 450 mbar, have a size of 0.15 μm in modal radius, and have a column abundance of 2.4×10^{8} cm^{-2} in the 1–350 mbar region. The particle abundance at deeper layers does not affect the computed reflectivities at both the 1.7 and 2.3 μm bands, as much of the light is absorbed at upper layers because of strong methane absorption. In the calculations made here, we employed a particle column concentration of 8×10^{11} cm^{-2} at the layer between 350 and 450 mbar. Modeling of Jovian reflectivities in the near infrared is complicated because methane absorption does not follow a simple Beer's law. This problem can be solved, however, by expressing the gaseous transmission as a sum of exponentials. This approach has been used by *Baines et al.* [1993], who presented exponential-sum fittings to the laboratory methane absorption measurements by *Giver et al.* [1990]. The technique was applied by us to both the laboratory measurements by Giver and by Strong [*Strong et al.*, 1993]. In addition to methane absorption, H_2-H_2 and H_2-He collision-induced absorption is another source of opacity in the near-infrared. We included these features using

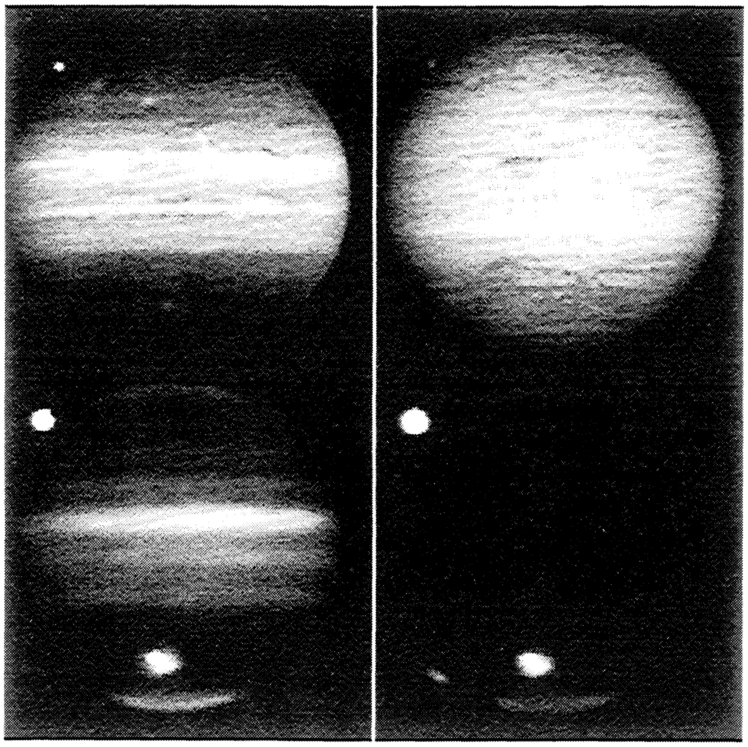

Figure 1. Set of images at 1.5, 1.58, 1.7 and 2.3 μm (from upper left to lower right) obtained on July 18th. The images at 1.5 and 1.58 μm have been deconvolved in order to show the impact areas, which are not easy to distinguish from unperturbed regions despite the high spatial resolution even in the case of the large D/G impact scar. The scar close to Central Meridian is the D/G complex. The scar appearing from the morning terminator corresponds to the H impact, some minutes after occurring. The UT times at which these images were obtained are: 20:12, 20:11, 20:04, and 20:01.

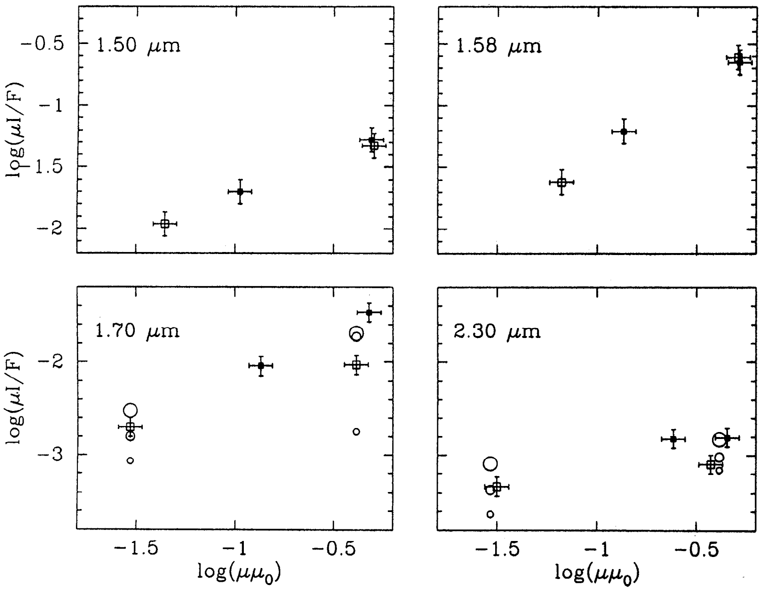

Figure 2. Observed reflectivities corresponding to the H and D/G scars (squares and filled squares respectively) at several geometries, for the wavelengths shown in each graph. Open circles are model reflectivities for particle column abundances of 1.2 $10^8 cm^{-2}$, 2.4 $10^8 cm^{-2}$ and 4.8 $10^8 cm^{-2}$ (the larger the circle, the higher the concentration).

the FORTRAN codes kindly made available to us by A. Borysow [*Borysow*, 1991, 1992]. Our model produces synthetic spectra for a given geometry with a spectral resolution of 10 cm^{-1}. Ammonia absorptions at 1.5 and 2.0 μm were not included in these models.

4. Model results and discussion

The model with a particle column abundance of 2.4 x 10^8 cm^{-2} in the 1-350 mbar region and imaginary refractive index of 10^{-4} is capable of reproducing most of the features of the observed H-scar spectra as well as its overall shape (figure 3). The agreement is worse toward the shortest wavelengths, which are sensitive to the properties of deeper-level Jovian clouds (poorly constrained here). As seen in figure 2, this model also fits the results from our images at 2.3 and 1.7 μm.

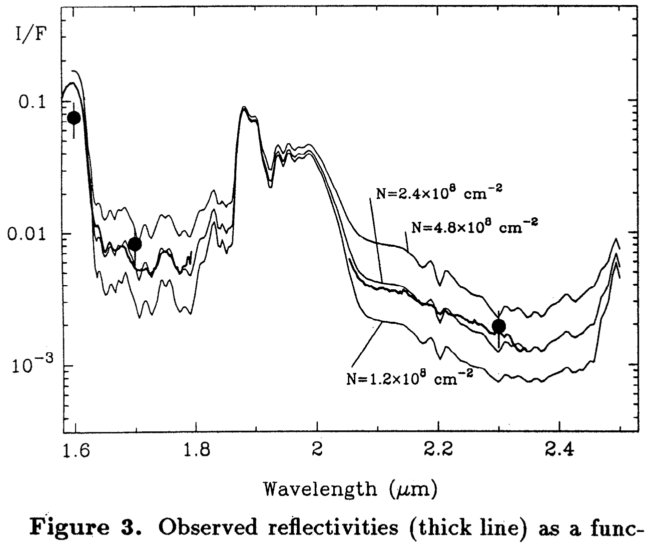

Figure 3. Observed reflectivities (thick line) as a function of wavelength for the H scar and modeled reflectivities convolved to the resolution of the measurements. The thin lines correspond to particle column abundances of 4.8 $10^8 cm^{-2}$, 2.4 $10^8 cm^{-2}$ and 1.2 $10^8 cm^{-2}$. Filled circles correspond to the imaging data at the same geometry.

The imaginary refractive index reported here is lower than those obtained for shorter wavelengths by *Moreno et al.* (this issue). The wavelength dependence of this parameter rules out astronomical graphite or astronomical silicate as the major component of the impact hazes, and favors energetic particle or UV irradiated hydrocarbons gas mixtures [*Khare et al.*, 1987] which have low IR imaginary refractive indices. The formation of these aerosols could be driven by the same mechanism which acts in generating the Jovian polar caps, because they show similar spectral characteristics. However, we cannot rule out mixtures of other compounds as the main constituent of the scatterers.

We show two additional model spectra for a higher and a lower concentration of particles (figures 2,3). A higher concentration of aerosols may be responsible for the higher reflectivity seen at the largest impact areas (one of which is the D/G complex). The upper level where the haze begins seems to be the same for all the impact scars, since this parameter mostly affects the depth of the 2.3 μm band, which is almost the same in the D/G complex. This might favor again a photochemical or ionization origin for the aerosols rather than one due to condensation. We also tried to retrieve the observed reflectivities using a model with larger particles and lower real refractive indices. We computed a model for a particle distribution of 0.5 μm in modal radius and N=2.16x10^7 cm^{-2}, with a real refractive index of 1.1. Although the modeled spectra are very close to the nominal model in the 2.3 μm region, the reflectivity in the 1.75 μm methane band is too low. The lifetime of the scars seems to be very long, which favors

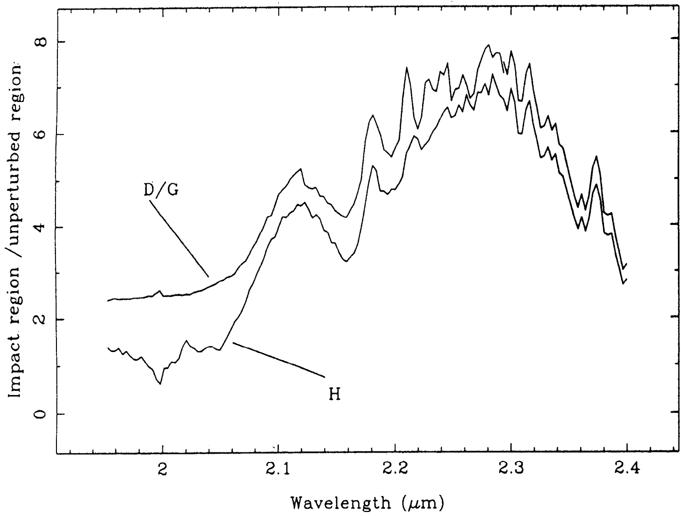

Figure 4. Ratios of spectra from the impact regions to spectra from unperturbed regions at the same geometry as those of the scars. The absorption feature at 2.0 μm is not present in the D/G scar.

smaller particles because of their longer sedimentation time. We therefore conclude that the cometary debris is best modeled with a distribution of small particles (0.15 μm in radius) for a real refractive index of 1.7.

Concerning the impactors' sizes, assuming that all the haze particles came from the comet, and an impact-core area of 5.3×10^6 km^2, the lower limit of the H impactor diameter is 230 m, as pointed out by *Moreno et al.* (this issue). Considering just the particles in the range of pressures probed by the 1.7 and 2.3 μm bands, the diameter would be 70 m. The G impactor would be even larger because the reflectivity of the G scar is higher at 2.3 μm.

We have computed ratios of H-scar spectra to spectra from unperturbed regions with the same geometry. The results are shown in figure 4. We find an increase in absorption at 2.0 μm for the H impact site, in each of the frames analyzed but not in the older D/G impact site. We believe this feature is due an increase of NH_3 abundance, but can not rule out an increase of H_2O abundance, since H_2O also absorbs at these wavelengths. NH_3 may have been lifted from the Jovian NH_3 ice haze as a result of the impact.

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References

Baines, K. H, R. A. West, L. P. Giver and F. Moreno, Quasi-random narrow band model fits to near-infrared low-temperature laboratory methane spectra and derived exponential-sum absorption coefficients. *J. Geophys. Res.*, *98*, 5517–5529, 1993.

Borysow, A., Modeling of collision-induced infrared absorption spectra of H_2-H_2 pairs in the fundamental band at temperatures from 20 to 300 K. *Icarus*, *92*, 273–279, 1991.

Borysow, A., New model of collision-induced infrared absorption spectra of H_2-He pairs in the 2–2.5 μm range at temperatures from 20 to 300 K: an update. *Icarus*, *96*, 169–175, 1992.

Giver, L.P., Benner, D.C., Tomasko, M.G., Fink, U., Kerola, D. Gaussian quadrature exponential sum modelling of near infrared methane laboratory spectra obtained at temperatures from 106 to 297 K. *NASA CP 3077*, 147–156, 1990.

Herbst, T.M., and J.T. Rayner. In Infrared Arrays: The Next Generation. Kluwer, p. 515, 1994.

Herbst, T.M., Hamilton, D.P., Böhnhardt, H. and J.L. Ortiz. Near infrared imaging and spectroscopy of the SL-9 Impacts from Calar Alto (this issue).

Khare, B.N., C. Sagan, and W. R. Thompson, Solid Hydrocarbon aerosols produced in simulated uranian and neptunian stratospheres. *J. Geophys. Res.*,*92*, 15067–15082, 1987.

Neckel, H. The absolute energy distribution of the Sun, of the "solar analogs" 16 Cyg B, Hyades VB 64, 16 Cyg A and of the standard stars α Lyr and 29 Psc. *Astron. Astrophys.*, *159*, 175–188, 1986

Moreno, F., A. Molina and J. L. Ortiz, Recent multispectral Observations of Jupiter from 0.6 to 2.4 μm. *J. Geophys. Res.*, *98*, 18837–18845, 1993.

Moreno, F., Muñoz, O., Molina, A., López-Moreno, J.J., Ortiz, J.L., Rodriguez, J., López-Jiménez, A., Girela, F., Larson, S., Campins, H. Physical properties of the aerosol debris generated by the impact of fragment H of comet P/Shoemaker-Levy 9 on Jupiter (this issue).

Stamnes, K., Tsay, S.C., Wiscombe, W. and Jayaweera, K. Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media. *Appl. Optics*, *27*, 2502–2509, 1988.

Strong, K., Taylor, F.W., Calcutt, S.B., Remedios, J.J. and Ballard, J. Spectral parameters of self- and hydrogen-broadened methane from 2000 to 9500 cm^{-1} for remote sounding of the atmosphere of Jupiter. *J. Quant. Spectros. Rad. Transfer*, *50*, 363–429, 1993.

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