

## FINAL REPORT

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"Mid-IR spectroscopy of the Jovian stratosphere perturbed by comet P/Shoemaker-Levy 9 impact"

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*Summary* – The objective was to obtain spectra from 5 to 14  $\mu\text{m}$  before, during, and after the impacts. We were awarded 2 flights of the KAO which was based in Melbourne, Australia for the events. Impacts *R* and *W* were covered, and the observations were completely successful. A paper reporting the observation of water vapor is in press (Sprague *et al.*, 1996), and other work is in progress as limited funding permits. The text of this report is adapted from that of the *Icarus* paper.

*The data set*

Our KAO data set consists of 103 spectra from Jupiter and our calibration stars. Observations were made on July 21 and 22, 1994. Data were taken at 39,000 ft (11.7 km), increased later in the flight to 41,000 ft (12.3 km). The HIFOGS spectrograph has been used on the KAO, the NASA 60-inch telescope at Mt. Lemmon near Tucson, and the IRTF at Mauna Kea for a variety of infrared observations including cometary dust, accretion disks, planetary atmospheres and surfaces. It integrates simultaneously in a linear array of 120 discrete detector channels. The array can cover nearly a full spectral octave at resolving power 130 - 230. The Si:Bi detectors are sensitive from 4.5 to 18  $\mu\text{m}$ . For our KAO flights we used HIFOGS in two different grating and filter configurations: 90 groove/mm for 4.8 - 9.3  $\mu\text{m}$  with a 4.6  $\mu\text{m}$  cuton filter, and 75 grooves per mm with an appropriate filter for 9 - 14  $\mu\text{m}$ . The integration time for one spectrum was  $\sim$ 89 sec and the cycle time  $\sim$ 3 min. Wavelength calibrations were made after each grating shift.

Our data set benefits from being absolutely calibrated in flux by comparison to  $\alpha$  CMa and  $\alpha$  Cen 1. Both stars have been well-calibrated by Witteborn and colleagues (Cohen *et al.*, 1992), and are known to be free of molecular absorptions in their atmospheres. Both stars were obtained at close to the same elevation angle as Jupiter (43-45 $^\circ$ ) during the flight.

Once Jupiter was acquired we began a predetermined sequence of observations of the *R* site beginning with the 4.6 - 9.4  $\mu\text{m}$  spectral region. Integrations lasted 1 min 29 sec with 45 sec on source. We alternated between short wavelength settings from 0521 to 0559 UT at which time we began our longer wavelength observations. The program for the *W* event on July 22 was similar, but the last short-wavelength spectrum was obtained at 0816 UT, 10 min after the impact.

Several additional spectra were obtained on Feb. 11 before any of the impacts, and between Aug 8 - 13 following the impacts, all with the same instrument at the NASA 1.5 m on Mt. Lemmon. The long time delay before the August run was principally attributable to U.S. Customs, which was unwilling to accept the HIFOGS packages even though they are U.S.-built and government-owned. Since August is the peak of the rainy season in Arizona, we were lucky to get even the few observations we did. No serious analysis has been possible yet, but the spectra seem to show the signature of silicate dust.

*Data Analysis*

The grant included almost no support for analysis, but for completeness we report progress to date, mostly supported by other grants. To our astonishment, our proposals to NASA and NSF for such work were not funded, so very little is being done currently.

*Calibration and atmospheric correction*

We have completed the calibration and atmospheric correction for the short-wavelength data set. All Jovian spectra are divided by and calibrated to  $\alpha$  CMa spectra obtained several minutes earlier. Flux calibrations are accurate to the extent to which  $\alpha$  CMa is known, a few %. Of primary interest is the absolute

flux emanating from the impact region itself. For the KAO flights we used a spectrograph aperture equivalent to 10.6 arcsec on the sky, considerably larger than the 4 arcsec (FWHM) image size. Thus the impact spot was entirely contained within our spectrograph aperture. During most of the peak flux integrations, the flux from the impact spot so exceeds the quiescent Jupiter that little correction is required to know the flux from the impact region; calculation of its radiance requires additional information or assumptions. During times when the contribution from unperturbed Jupiter is significant (for example, just before an impact), some of the aperture contains cold sky off Jupiter's limb. By reviewing the video tapes made at the guiding telescope for the duration of both flights Witteborn and KAO personnel have been able to estimate filling factors for the field of view during spectral integration. The aperture's center was slightly off the limb for  $R$ , with a typical filling factor of 0.23; for  $W$  it was 0.56.

For the ground-based pre-crash measurements the absolute calibrations are good to a few percent; skies were clear and standard stars were well-calibrated. For the post-crash measurements in August, calibrations suffer from changeable cirrus clouds but we estimate that they are good to within 10% or so.

Comparison of pre-crash spectra from several locations on Jupiter with the Voyager spacecraft data obtained with IRIS including the same spectral region has demonstrated the excellent performance of HIFOGS and the reproducibility of known features at previously measured locations. The same good reproducibility is found with KAO data obtained from the northern hemisphere of Jupiter, remote from the impact sites.

Calibration of the long-wavelength data set is more complicated because the signal-to-noise ratio in data for the standard stars ( $\alpha$  CMa and  $\alpha$  Cen A) is low owing to limited flight time and the low flux of the stars between 9 and 15  $\mu\text{m}$ . Thus we cannot make a straightforward ratio to both remove the residual absorptions from the atmosphere above the airplane and simultaneously absolutely calibrate the flux. Atmospheric corrections must be made using the ATRAN program for modeling the absorptions above the KAO. Absolute flux calibrations can be made in two ways:

1. by comparison with spectra of the on-board heated resistor obtained at regular intervals between Jovian measurements, and
2. smoothing the standard star spectra and using the resulting spectrum for our ratios to Jupiter data then correcting residual telluric atmospheric absorptions using the ATRAN model spectra.

### *Data Interpretation*

The data are rich with information regarding the time-history of major and minor emitting species: some identified and others not. Unique to KAO data is good information on water vapor, and our paper on our detection and interpretation has been accepted by *Icarus* (Sprague *et al.*, 1996). Another paper from the other three KAO flights is also under review (Bjoraker *et al.*, 1996). Preliminary reduction and modeling also shows emission features from  $\text{CH}_4$ ,  $\text{NH}_3$ ,  $\text{C}_2\text{H}_2$ ,  $\text{C}_2\text{H}_6$ , dust and aerosols, and possibly  $\text{SO}_2$ ,  $\text{H}_2\text{S}$ ,  $\text{C}_2\text{H}_4$ , silicates and  $\text{N}_2\text{O}$ .

Almost immediately we noticed an anomaly in the region of the 7.65  $\mu\text{m}$   $Q$  and  $P$  branches of  $\text{CH}_4$  in spectra following both impacts. Attempts to explain it have been the focus of our attention and are fundamental to any attempts to model the chemical and physical effects of the impact region. Very recently we have discovered a likely explanation: the presence of molecules or particles sometimes called UIR (Unidentified InfraRed) and plausibly identified as polycyclic aromatic hydrocarbons or PAHs (Witteborn *et al.*, 1989). They are observed in some carbon-rich astronomical objects. In addition to a strong emission feature just longward of (and blended with) the  $\text{CH}_4$   $Q$  branch, they probably explain other peaks observed in our spectra at 6.2, 8.6 and 11.3  $\mu\text{m}$ . A spectrum of NGC 7027 also obtained with HIFOGS has been compiled by Wooden. Very notable are UIR or PAH emission features at 6.2, 7.7, 8.6 and 11.3  $\mu\text{m}$ . Other gaseous emission lines are also present. Spectra from our SL-9 data set for  $W + 11$  and  $W + 16$  minutes show features similar to those of the PAHs in NGC 7027, especially at 6.2 and 11.3  $\mu\text{m}$ . Finally we believe we have the explanation for the broad and oddly shaped methane feature: it is mixed with PAH emissions spanning the same wavelengths. It must however be pointed out that instrument PI Fred Witteborn still has concerns about the reality of some of the peaks discussed above.

### *Future intentions and hopes*

Depending on our ability to obtain adequate support, we hope to complete the long wavelength calibration, and then to proceed with the modeling and interpretation of our many excellent spectra to enable:

1. identification and measurement of the abundances of the emitting species. Some are known but only water has been adequately modeled to obtain abundance. We believe there are features present of other oxidized species such as SO<sub>2</sub>, NO, OCS in the 5 – 11  $\mu\text{m}$  region and several hydrocarbons at longer wavelengths, some of which are not yet identified. There are many peaks that appear following the impacts, then die away. In particular, we have so far concentrated almost entirely on the short-wavelength spectra and must now turn our attention to the long-wavelength range.
2. characterization of the PAH features at approximately 6.2, 7.9, 8.6 and 11.3  $\mu\text{m}$  and construction of light curves for the *W* event where they are prominent; completion of a search for them in the spectra of *R*.
3. formulation of a coherent picture of the chemistry in the fallback plume following the *R* and *W* impacts. We have already determined that the plume fallback region had to have been heterogeneous in composition because we see abundant water and the Hubble Space Telescope saw abundant S<sub>2</sub>.
4. refinement of our recipes for the composition of the impacting objects. We have already determined that carbon-rich silicate and water must have been ingredients of the impacting bolides *R* and *W*. After we have completed our modeling and analysis of the PAHS we can use that measurement to refine our comet model.
5. interpretation of the large increase in C<sub>2</sub>H<sub>2</sub> emission present in our long wavelength spectra hours after the impacts with an aim of determining if this represents a true increase in abundance. This would be consistent with an increased inventory of PAHs brought in to Jupiter's atmosphere by SL-9 and we wish to explore this possibility.
6. characterization of the continuous emission from dust, obtaining its spectrum as a function of time. We are exploring a collaboration with the Cornell group (Nicholson *et al.*) who have complementary data.
7. explanation for the peculiar C<sub>2</sub>H<sub>6</sub> emission between 10.6 and 12.6  $\mu\text{m}$ . It appears to be severely suppressed relative to pre-crash Jovian conditions in both our ground-based and KAO data obtained following the impacts. We do not know if this is a result of chemistry or some other effect like dust absorption in that spectral region. We expect that further modelling will help us to understand this behavior.
8. development of a physical model of the luminous phenomenon and its evolution. Key parameters are the temperature and composition (possibly including inhomogeneities) as functions of time. We feel that our data, covering almost the entire spectral region of molecular vibrational fundamentals, will be essential inputs to this process. Other inputs will come from the Galileo NIMS and imaging experiments; light curves at a variety of wavelengths; inferences concerning dust; molecular identifications by other observers; and chemical modeling,

Achievement of these goals will require Sprague (and a student assistant) to continue to use the SSP program to model the many spectra. We believe it is the best choice for the modeling. It calculates line-by-line emissions and absorptions, can handle dust continuum emissions and absorptions, permits the specification of a large number of layers with different temperatures and compositions, and can handle the spherical geometry of the limb. Sprague will coordinate interaction between herself, Hunten, Bjoraker, Witteborn, Wooden and Kozlowski for interpretation of models and subsequent theoretical studies that may arise from new discoveries.

### References

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