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Direct observations of the Comet Shoemaker-Levy 9 fragment G impact by Galileo UVS

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Abstract. The Galileo Ultraviolet Spectrometer (UVS) team has detected the Shoemaker-Levy 9 fragment G impact on Jupiter in data recently played back from the spacecraft tape recorder. A 20% brightening of the disc-integrated signal of Jupiter was detected at 292 nm during a swath across Jupiter that lasted 1.6 sec and was centered at 1994-July 18 (day 199)/07:33:31 UT (all times in this paper are corrected to be the time of the event as seen from Earth). The emission brightness, when combined with simultaneous Photopolarimeter Radiometer (PPR) measurements at 945 nm, is consistent with thermal radiation at a temperature of 7800 (+500, -600) K emitted over an area of 40 (+60, -25) km^2. No excess signal was seen during swaths 5 1/3 sec before and after the detection swath.

Introduction

The Galileo spacecraft (Johnson et al., 1992) witnessed the unique Comet Shoemaker-Levy 9 (SL9) impact events on Jupiter. The sun-Jupiter-spacecraft phase angle of 51 deg provided direct viewing of the fragment G impact event, which occurred just before dawn beyond the limb of Jupiter as seen from Earth. The G impact site was at planetocentric latitude -43.66±1.0° and system III longitude 26.8±2.0° (Hammel et al., 1995). Three Galileo scan platform instruments: the Near-Infrared Mapping Spectrometer (NIMS), the PPR, and the UVS performed simultaneous, boresighted measurements during the period when the impact of fragment G was expected. The scan platform swept the instrumental fields of view across Jupiter from the dark to bright limb and then back in a pattern that repeated every 10 2/3 sec. This paper will briefly discuss and interpret the UVS detection of the fragment G impact event.

Experimental Design

The UVS observing strategy for the fragment G observation was chosen to search for thermal blackbody emission from the impact event. The Galileo UVS instrument uses a Cassegrain telescope, an Ebert-Fastie spectrometer, 3 photomultiplier tubes and a scanning grating drive to record UV spectra from 115-430 nm (Hord et al., 1992). The UVS F-channel has a photomultiplier tube with a cesium telluride photocathode (160-320 nm) and is suitable for observing planets illuminated by sunlight. Above 300 nm the sensitivity of this tube drops sharply. An F-channel fixed wavelength of 292 nm (1.4 nm band pass), near the peak response to Jupiter (Fig. 1), was chosen to maximize the probability of detecting thermal emission from the impact. This wavelength is at the energy emission peak for blackbody thermal radiation at a temperature of 10^4 K. There are no distinctive absorption or emission features in the reflected solar spectrum at 292 nm.

During the fragment G observation on July 18, 1994, Galileo was 240 million km from Jupiter, whose angular diameter was 0.034 deg. The planet underfilled the UVS instrument slit (0.10° x 0.33°). The angular rate of the scan platform sweeps was such that Jupiter traversed the 0.1° width of the UVS slit in about 1.6 s. The observing geometry is shown in Fig. 2. Brightness measurements were reported every 7.6 ms, each representing 6 ms of integration.

Observations

Galileo UVS data at 292 nm from 73 full or partial 1.6 s traverses across Jupiter were returned to Earth. Of this set, 33 were sequential swaths from the period 1994-199/07:33:12 to 07:36:06. A total of 53 swaths were used (including the detection swath) in this analysis. The whole data set spanned the period from 07:31:44 to 07:41:51. The average count rate from 52 such traverses (with no evidence of excess signal) was 6.6 counts per 6 ms at 292 nm, corresponding to an energy flux at Galileo of 2.1×10^{-14} watt cm^{-2} nm^{-1}. Only one traverse across Jupiter at 1994-199/07:33:31, detailed below, produced UVS count levels significantly different from the average. The average count levels for each traverse were distributed according to Poisson statistics, as expected, except for the one bright swath. Jupiter measurements 5 1/3 s earlier and 5 1/3 s later than the bright swath were not significantly different from the other background Jupiter measurements, indicating that the UV flash was brief.

The impact flash was seen during a right-to-left traverse of Jupiter across the UVS field of view. On such traverses, the terminator crossed into the slit first, followed 0.45 s later by the bright limb. The average of 15 such traverses, not including the impact traverse, is shown in Figure 3 as a heavy line. Also plotted is the impact traverse; both curves have been smoothed over 13 samples or 0.1 s. All the traverses were hand-aligned before the average was taken, to counteract the effects of small errors in pointing and/or timing. The RMS correction was 0.09 mrad or 80 ms. The impact site entered the slit 0.42 s before the bright limb, making the impact swath wider than the background swaths. In Figure 3 the impact traverse was aligned with the average at the right-hand edge, after the impact site had left the field of view. The difference between these two curves is shown as a histogram representing the average excess counts seen in successive 0.1 s

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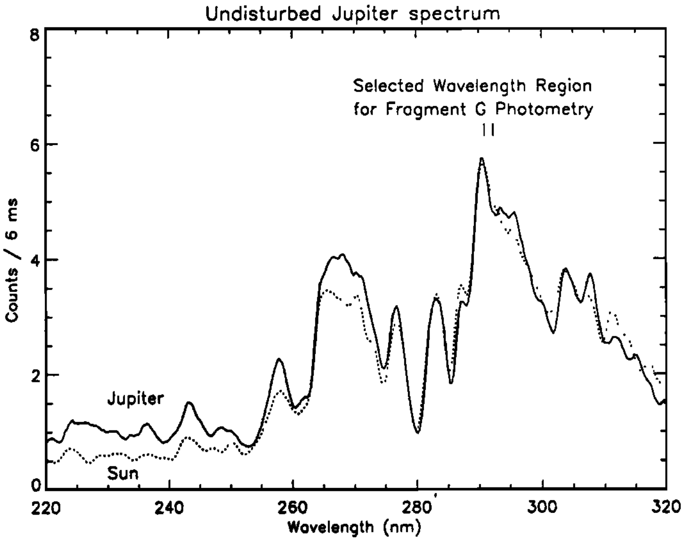

Figure 1. A Galileo UVS F-channel disc-integrated undisturbed spectrum of Jupiter obtained on 1994 day 195. An estimate of the scattered light contribution has been subtracted. The fixed wavelength of 292 nm selected for the G fragment observation is indicated. A SUSIM solar spectrum (Van Hoosier et al., 1988) is also shown, degraded in wavelength to match the Galileo UVS 1.4 nm resolution. The solar spectrum has been convolved with the UVS wavelength response function to simulate an observation of the sun and then arbitrarily scaled. Jupiter is bluer than the sun from 2400-3200 Å, as found in earlier work (Wagener et al., 1985).

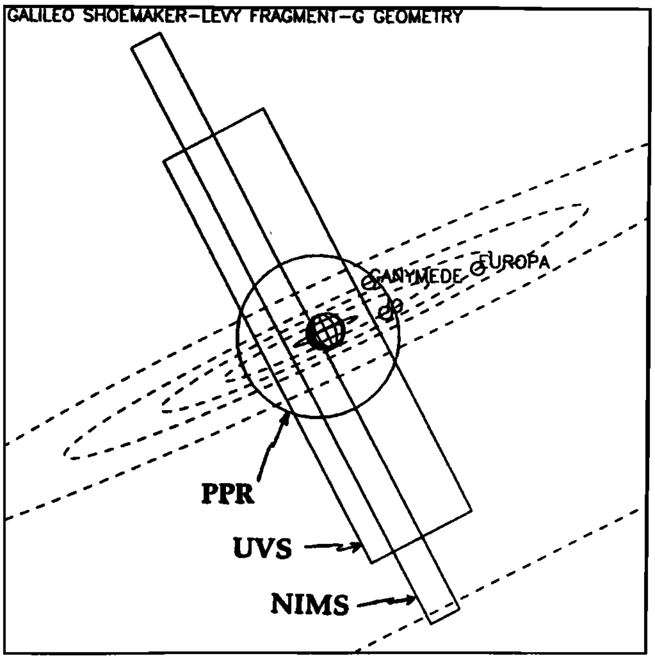

Figure 2. The observing geometry for the G fragment experiment showing Jupiter is much smaller than the Galileo UVS slit which is swept across it at right angles to the slit length. During the detection swath the slit encountered first the dark limb of Jupiter then the bright limb. The Galileo NIMS and PPR instrumental fields of view are also indicated.

intervals. The best straight-line fit to the 16 intervals containing the impact flash is also plotted. The average excess is 1.33±0.29 counts/6 ms, or 20% of the signal from Jupiter itself.

1-σ error bars based on the counts in the 0.1-s intervals are shown on two representative intervals. The standard deviation of the residuals about the best fit is 1.2 counts/6 ms, very close to the 1.3 counts/6 ms expected on statistical grounds. While variations in the flash brightness cannot be excluded, only the residual near 1.4 s elapsed time deviates significantly from a normal distribution.

Figure 4 compares the count levels on 52 traverses (15 right-to-left, 37 left-to-right) with the impact traverse. Many traverses contain data dropouts, and the values in Figure 4 are for the central 1.25 s of each traverse, where the count rates are flat and dropouts are therefore easily allowed for. Excluding the impact traverse, the average of these points is 6.61 counts/6 ms with a standard deviation of 0.20. The flash brightness of 1.33 counts/6 ms thus represents a 6-σ detection. (Because the traverse of the impact flash across the UVS field of view did not fully overlap the 1.25 s sampling interval, the impact traverse shows an excess of only 1.11 counts/6 ms in Figure 4.) The UVS observation at 292 nm coincides with the initial rise in signal observed by the Galileo PPR at 945 nm on the same traverse across Jupiter (Martin et al., 1995). The PPR data, suitably scaled, are also shown in Figure 4. The Galileo NIMS first detected an enhanced signal on the subsequent traverse, 5 1/3 s later (Carlson et al., 1995).

Interpretation

Comparison of the data from the Galileo NIMS, PPR and UVS instruments determines the thermal history and total radiative output of the G impact. The UVS excess signal of (4.3 ± 0.9)x 10^{-15} watts cm^{-2} nm^{-1} at the spacecraft occurred at the same time that PPR recorded an initial excess signal of (1.1 ± 0.2)x10^{-15} watts cm^{-2} nm^{-1} at 945 nm (Martin et al., 1995). This leads to an energy flux ratio $E_{292\ nm}/E_{945\ nm}$ of 3.9 ± 1.1, which is characteristic of thermal blackbody radiation at 7800 (+500, -600) K. There is some uncertainty in the 945 nm excess (see Martin et

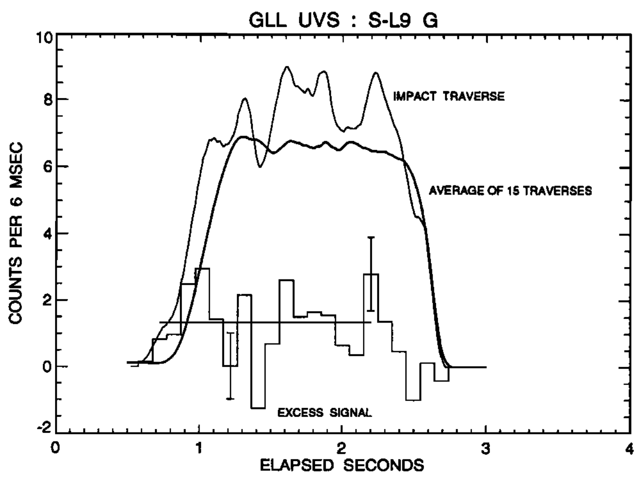

Figure 3. The UVS detection swath across Jupiter and the average of 15 similar swaths are shown. Each has been smoothed by 0.1 s. A histogram of the difference between the two curves is also shown. The straight line is a least-squares fit to the excess counts, its length indicates the traverse of the impact site across the UVS field of view. Note the displacement to the left of the excess counts due to the flash, caused by the displacement of the impact site from Jupiter's center of light.

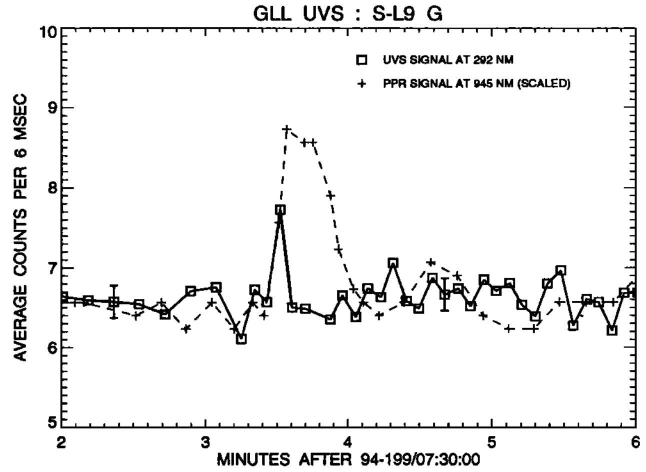

Figure 4. Counts per 6 ms at 292 nm averaged over 1.25 s are shown as one point per traverse of the UVS slit across Jupiter (□). The error bars indicate the standard deviation of 52 normal traverses. Note the bright traverse associated with the fragment G impact. Simultaneous PPR data points have been scaled for comparison and are marked (+).

al., 1995, footnote 8). Should the infrared excess at 945 nm be twice the reported value, the corresponding temperature would be ~6700 K. The assumption that thermal blackbody emission is present is generally consistent with the Carlson et al. 1995 (NIMS) 0.7-5.0 μm fireball spectra obtained beginning about 5 1/3 s after the UVS detection. These NIMS spectra show a black-body spectrum with superimposed absorption features. Because of the back and forth scan platform motion, we do not know if higher temperatures existed between measurements when Jupiter was not in the UVS field of view. For example, models by Crawford et al., 1995 find temperatures at the leading edge of the cometary projectiles as large as 35,000 K. Ahrens et al. 1994 predicted bolide temperatures of more than 10,000 K. A direct measurement of the bolide flash temperature by Galileo PPR (two-color photometry at 678 and 945 nm) on the Q1 fragment found an initial temperature of ~18,000 K (Martin et al., 1995). The total thermal radiation emitted by impact G during the 1.6 s of UVS detection, assuming a blackbody at 7800 K, is 1.6×10^{16} joules. For comparison, a kiloton of TNT = 4.2×10^{12} joules, so the thermal radiation emitted was equivalent to 3800 kilotons of TNT.

By 5 1/3 s after the UVS flash, the PPR signal increased to its peak level of $(2.2 \pm 0.2) \times 10^{-15}$ watts $cm^{-2} nm^{-1}$, but the UVS signal had dropped to its pre-impact background level, where it remained for the rest of the time period covered in the data returned to Earth. This suggests that the emissions had cooled substantially, shifting the emission peak in the blackbody spectrum to longer wavelengths. From the non-detection by the UVS we can set a 2-σ upper limit on the temperature for this subsequent swath of ~5500 K. Smythe et al. 1994 (NIMS) found a temperature greater than 5000 K for this same swath.

The flux at the Galileo spacecraft at two wavelengths uniquely determines both the temperature and the area of the emission, assuming purely thermal emission. The hot emitting area required to produced the flux at 292 nm of the UVS bright swath given the derived temperature is found to be 40 (+60, -25) km^2 assuming a reflecting layer below the blast scatters the emission into the upward hemisphere. The actual geometry is unclear: the derived area may refer to a long narrow trail of hot gas created on entry or to a more spherical fireball. This area determination is consistent with the Carlson et al., 1995, (NIMS) emitting area determination of 1250 km^2 for the swath 21 s later if the hot gas had cooled and expanded. NIMS actually monitored the expansion and cooling of the fireball for several minutes.

Summary

The UVS experiment observing at 292 nm shows that a brief initial UV flash was produced by the G fragment when it entered Jupiter's atmosphere. The initial flash was also detected by Galileo PPR at 945 nm (Martin et al., 1995), allowing us to estimate an initial temperature of ~7800 K from the UV/IR flux ratio. The UVS bright point falls on the rapidly rising part of the PPR light curve, which may correspond to the fast passage of the fragment through the visible part of the atmosphere (Martin et al., 1995). If this is the case, the UVS data probably represents thermal radiation emitted by the bolide as it descended into the atmosphere. A bolide traveling 60 km/s at an approach angle of 45 degrees traverses an altitude range of (60 km/s) x (1.6 s) x cos(45°) ~ 70 km during the 1.6 s period of UV signal. By the subsequent swath 5 1/3 s later the affected hot atmosphere had expanded and cooled enough so that its thermal emissions were below the UVS detection threshold at ~5500 K. Further expansion of the hot gas led to the spectacular limb plumes observed by the Hubble Space Telescope (Hammel et al., 1995). The Galileo NIMS team (Carlson et al., 1995) reported a subsequent "fall back" event at 1994-199/07:39:41 UT as the plumes were recompressed and heated by gravity. The UVS experiment did not detect this secondary event, which involved cooler gas and redder emissions than the initial impact.

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