Galileo observations of the impacts

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Galileo observations in the UV, visible, and infrared uniquely characterize the luminous phenomena associated primarily with the early stages of the impacts of SL9 fragments—the bolide and fireball phases—because of the spacecraft's direct view of the impact sites. The single luminous events, typically 1 min in duration at near-IR wavelengths, are interpreted as initial bolide flashes in the stratosphere followed immediately by development of a fireball above the ammonia clouds, which subsequently rises, expands, and cools from ~ 8000 K to ~ 1000 K over the first minute. The brightnesses of the bolide phases were remarkably similar for disparate events, including L and N, which were among the biggest and smallest of the impacts as classified by Earth-based phenomena. Subsequent fireball brightnesses differ much more, suggesting that the similar-sized fragments were near the threshold for creating fireballs and large dark features on Jupiter's face. Both bolides and fireballs were much dimmer than had been predicted before the impacts, implying that impactor masses were small ($\sim$0.5 km diameter). *Galileo* data clarify the physical interpretation of the "first precursor," as observed from Earth: it probably represents a massive meteor storm accompanying the main fragment, peaking $\sim$10 s before the fragment penetrates to the tropopause; hints of behind-the-limb luminous phenomena, recorded from Earth immediately following the peak of the first precursor, may be due to reflection of the late bolide/early fireball stages from comet debris very high in Jupiter's atmosphere.

1. Introduction

The *Galileo* spacecraft was in a unique position to observe the crash of Comet Shoemaker-Levy 9 (SL9) into Jupiter. Well on its way past the asteroid belt en route to its successful injection into Jupiter orbit in December 1995, *Galileo* was only 1.6 AU from Jupiter and offset $\sim$40.5° to the line-of-sight from Earth. Thus instruments on *Galileo*'s scan platform had a *direct view* of the impact sites (at tropospheric level) at the time of the impacts.

It was remarkable, of course, that Earth-based observers saw prominent early phenomena, despite predictions that most of the events would occur behind Jupiter's limb. Observed phenomena included brightenings prior to bolide entry, bolide entry, early development of the fireball, the rise of the cooling fireball/plume into direct view from Earth and then into solar illumination, and the vastly brighter subsequent splashback (see review by Nicholson, this volume).

All of the early-stage phenomena seen from Earth, however, were observed in ways that are difficult to quantify, being plagued by foreshortened geometry (made all the more ambiguous by uncertain altitudes of phenomena), intervening jovian atmosphere, tangential solar illumination, etc. *Galileo*, in contrast, had an unimpeded, direct view of the initial impacts and early phases of fireball development against the dark side of Jupiter. Therefore, despite the modest apertures of *Galileo*'s instruments, which could not compete with the major groundbased and Earth-orbital observatories, *Galileo* provides a reliable baseline on the initial luminous phases of the comet fragment impacts. The later phases, such as the solar-illuminated plume and the splashback, were near or below the *Galileo* camera's detection threshold; eventually, analysis of *Galileo* infrared

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https://doi.org/10.1017/S0252921100115489 Published online by Cambridge University Press

observations of the splashback may supplement the direct observations made from the Earth as Jupiter's rotation brought the impact regions into good viewing geometry.

The early-stage, luminous phenomena are crucial for characterizing and understanding the impacts and the development of later stages. Prior to striking Jupiter at 60 km s^{-1}, the comet fragments were—compared with the spatial scale of later-stage phenomena on Jupiter—very compact objects, or clusters of objects. They gave up most of their appreciable kinetic energies in seconds as they streaked down through Jupiter's atmosphere. Initially, only very small volumes of the atmosphere were heated and otherwise affected by the explosions. *Galileo* instruments helped to define the character of the conversion of the bolides into fireballs, and the early stages of fireball development, at times when there was particularly strong bias against Earth-based observations (because the fireballs were created deep in Jupiter's atmosphere, hundreds of kilometers below the projection of Jupiter's limb as seen from Earth).

The major *Galileo* contributions to SL9 observations came from three instruments—the Solid State Imaging system (SSI, the camera), the Photopolarimeter Radiometer (PPR), and the Near-Infrared Mapping Spectrometer (NIMS). In addition, the Ultraviolet Spectrometer (UVS) detected the initial seconds of at least the G impact. None of the instruments, except for the camera, had spatial resolution on Jupiter from this distance. So the PPR, NIMS, and UVS data on the impacts are essentially photometric observations of phenomena *added to* the signal from Jupiter itself. Despite this disadvantage, the signal-to-noise ratios were generally large for the major impacts, and the bolide and fireball phenomena were well characterized.

The SSI camera had significant spatial resolution on gibbous Jupiter, roughly equivalent to that of a modest groundbased telescope—59 pixels across Jupiter's diameter (2430 km $pixel^{-1}$)—although direct images were acquired for only one impact, that of fragment W (Fig. 1). The other recorded events (K, N, and V) were observed in a drift-scanning mode that provided spatial resolution in one dimension and a time-history of the brightness in the other. (Tape-recorded data for V have not been returned to Earth, although there is a remote possibility that they may be read back before they are overwritten in spring 1996.)

Limitations on the spacecraft prohibited the other instruments on *Galileo*'s scan platform from recording data simultaneously with SSI. Thus they observed a complementary set of impact events. The PPR obtained good data on fragments G, H, L, and Q1; other events were too weak to be detected, were played back with infrequent sampling intervals, or (for those judged likely to be too faint to detect) were not played back at all. The relatively data-intensive NIMS obtained infrared spectra only for the G and R impacts (data for two other weaker events were not returned to Earth).

Because of uncertain predictions of what would be observed, most *Galileo* instruments used a variety of strategies, within operational constraints, to observe the different impacts—varying filters, sampling frequencies, etc. Only a tiny fraction of all recorded data could be returned due to limited antenna capability (some data still remain on the spacecraft tape recorder as of this writing, February 1996, but probably will soon be overwritten by data from the Jupiter system). Thanks to prompt reporting of observations by groundbased observers using the SL9 Exploder on the Internet during the week of the impacts, it was possible to identify the events and crucial intervals of time for which it would be most useful to return data during the available period, August 1994 through January 1995. The resulting data set is a gold mine of unique information on the impacts.

Only preliminary reductions of the *Galileo* data have been published so far. SSI data for K, N, and W are summarized by Chapman *et al.* (1995a), but more data have since been

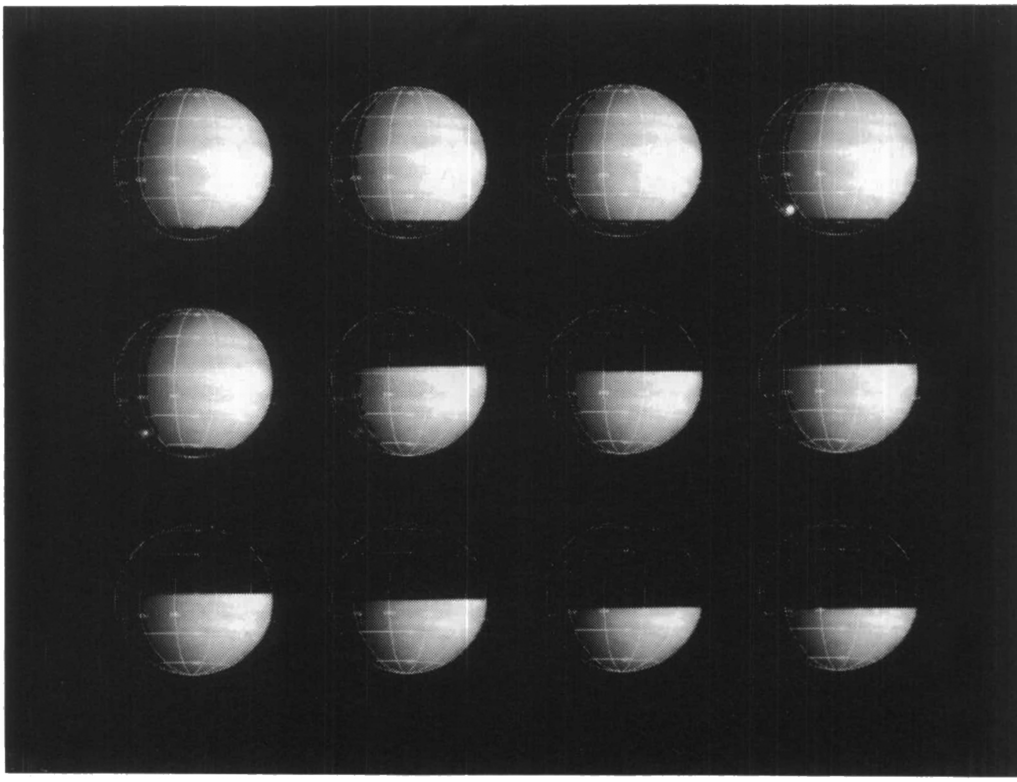

FIGURE 1. Galileo images of the W impact (0.56 μm). The first and last images were taken at 8:06:10 and 8:06:40 on 22 July 1994. The images are taken at intervals of 2.3 s except 7 s between images 5 and 6. The event is recorded on images 3 through 11. Missing portions of Jupiter are due to selective data return. A latitude/longitude grid is superimposed.

made available and refinements in the reductions are underway (Chapman and Merline, in preparation). The PPR observations are summarized by Martin *et al.* (1995), which includes refinements in interpretations developed at IAU Colloquium 156. A preliminary report on NIMS observations of the G event is by Carlson *et al.* (1995a); some of the NIMS R data are briefly discussed by Carlson *et al.* (1995b) as well as a light curve and spectrum for the beginning of the G splashback. Other preliminary reductions of NIMS data have been presented at various scientific meetings and in a recent book (Spencer, 1995). UVS observations of G are presented by Hord *et al.* (1995).

Intercomparison of the various *Galileo* data sets, among themselves and with ground-based data, has provided a clear picture of the early stages of the impacts, which I discuss in this chapter. The most important qualitative conclusions are that (1) the early luminous phenomena for the observed impacts had similar time histories, (2) they had unexpectedly similar luminosities despite wide variations in Earth-based observations of later phenomena, and (3) they were unexpectedly dim for the energies expected from the multi-km diameter fragment sizes that had been predicted prior to the events. Thus the *Galileo* observations support the conclusion of most researchers (see review by Mac Low, this volume) that the SL9 fragments were under 1 km in diameter. Furthermore, the NIMS observations of the G impact—a typical large event—characterize the history of the development of the fireball during the interval of time it was hidden from Earth-based observation. The G fireball started out very hot and small and was located in the upper

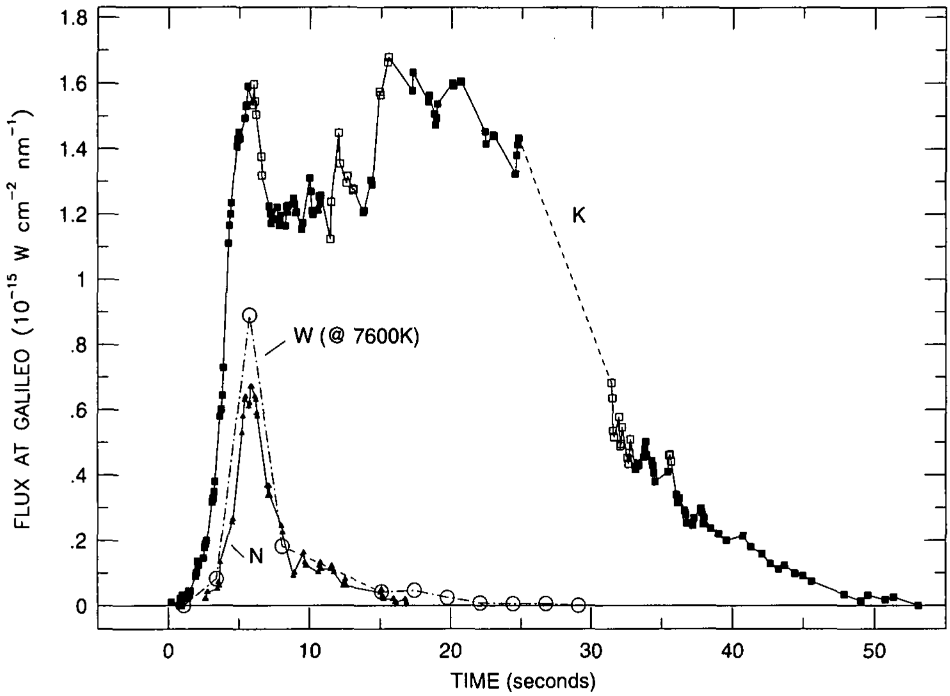

FIGURE 2. SSI light curves for K and N, observed at 0.89 μm. Data at 0.56 μm for W are plotted for comparison, assuming a 7600 K black body (likely to be approximately true near the initial spike, but not later in the event). Open symbols for K have larger uncertainties than solid points; dashed line is a data gap. For details, see Chapman *et al.* (1995a) from which this figure is adapted.

troposphere, just above the clouds; over the course of the next 70 s, it was observed to rise, expand, and cool, before fading from detectability by NIMS.

2. The *Galileo* observations

Galileo SSI data on impacts K, N, and W are shown in Fig. 2 (replotted from Chapman *et al.* 1995a, where more details may be found). Note that data for K and N were observed in the same mode (in the same 0.89 μm narrow-band methane filter, drift-scan mode); also note that the data for W (observed in a ~2.3 s time-lapse direct imaging mode through the broader 0.56 μm green filter) have been rescaled to correct for the difference in wavelength, using the best available *Galileo* photometric calibrations (good to ±15%), assuming that a 7600 K black-body color temperature applies during the bolide phase.

The peak brightnesses are dim, compared with pre-impact predictions that they might rival the brightness of Jupiter itself. For instance, W reached only ~1.5% of the brightness of Jupiter (at 0.56 μm). It is particularly noteworthy that the peak brightnesses of the events are similar, despite the very different characters of their later development as observed from Earth (K was one of the 3 biggest events, W intermediate, and N a minimal event). Impact N (class 3 in the Hammel *et al.* 1994, compilation) left only a tiny spot on Jupiter and was reported to be many hundreds of times fainter than K during the splashback phase. Nevertheless, N's peak brightness is down by only a factor of ~2.5 from the brightness of K as observed by SSI.

Comparison of the light curves reveals that they represent two distinct physical phenomena. An abrupt initial rise of the light curve, mostly occurring in just 2 s, is seen in

https://doi.org/10.1017/S0252921100115489 Published online by Cambridge University Press

all three light curves. It then immediately decays, on a similar timescale, to less than 20% of peak brightness. This initial "spike" was interpreted by Chapman *et al.* (1995a) as the bolide flash in Jupiter's stratosphere. Despite the similarity of the bolide spikes for K, N, and W, the subsequent luminosity behavior was dramatically different. For K, there was a 45 s-long period of prominent luminosity, peaking about 10 s later than the bolide at a brightness slightly exceeding that of the bolide. This can be confidently interpreted (through analogy with NIMS data at the corresponding time during the similarly-shaped light curve for G—see below) as the hot, early stages of the rising fireball, which soon cooled to temperatures at which 0.89 μm radiation was minimal. (The possibility that a sudden onset of the second peak is enhanced by a second impact, occurring 10 s after the first, cannot be discounted.)

In sharp contrast, the N event shows little or no evidence of a fireball phase. Since a "main event" splashback was recorded from Earth with the characteristic 6 min delay after impact (Meadows *et al.* 1995; McGregor *et al.* 1996), we presume that there was a small fireball for N but that it was simply near or below the detection limit for SSI. The W light curve from SSI looks very similar to that of N, but recall that W was observed at a shorter wavelength. Presumably observations of W at 0.89 μm would have shown a fireball light curve intermediate between N and K. Luminosity from W was followed through nearly 30 s, a longer duration than for N due to the lower detection threshold of the direct imaging observing mode.

Galileo PPR data (at 0.945 μm) for impacts G, H, L, and Q1 are shown in Fig. 3 (from Martin *et al.* 1995). Note that data were sampled less frequently for G, which was being simultaneously observed by other instruments. Because PPR data represent excesses over the brightness of Jupiter, they are noisier than the SSI observations, especially for the weaker Q1 impact. Nevertheless, the well-defined curves for G, H, and L look very much like the SSI curve for K, showing a sharp initial onset, followed by a plateau, and then a decline into the noise. The durations ($\sim$30 s) are similar to what would have been observed for K above the same background.

Given that the PPR data were taken at a wavelength very similar to that of the SSI data for K, it is likely that the light curves have the same interpretation, despite the fact that none of the PPR curves clearly shows the dip seen between the two phases for K. The sharp onset evidently is the bolide phase, which merges into a more extended initial fireball phase. (The possibility that the light curves for G, H, K, and L represent only the fireball phase following an invisible "stealth" bolide, raised by Martin *et al.* [1995] and others, is discussed below.) Just as for the events observed by SSI, the brightnesses of the four PPR events are very similar, all within a factor of three of each other. From the Earth-based perspective, Q1 was an intermediate event like W while L was the strongest event of all.

Comparing Figs. 2 and 3 (and making corrections for the slightly different wavelengths), it appears that K was a little weaker than H while N and W were about half the brightness of Q1. The range in brightness between the brightest event (L) and the faintest (N) is less than a factor of 5.

The K event observed by SSI might be thought to be a little dim in comparison with the PPR events, based on expectations from pre-impact fragment magnitudes and from the relative strength of subsequent phenomena observed from Earth. Orton (1995) shows an alternative comparison of the SSI and PPR data sets that makes K as bright as L, but his scaling via an 18,000 K color temperature is based on a faulty understanding (for which I accept responsibility) of how the SSI data were calibrated. Apparently, there are *real* differences among the impactors resulting in scatter by a factor of two or more

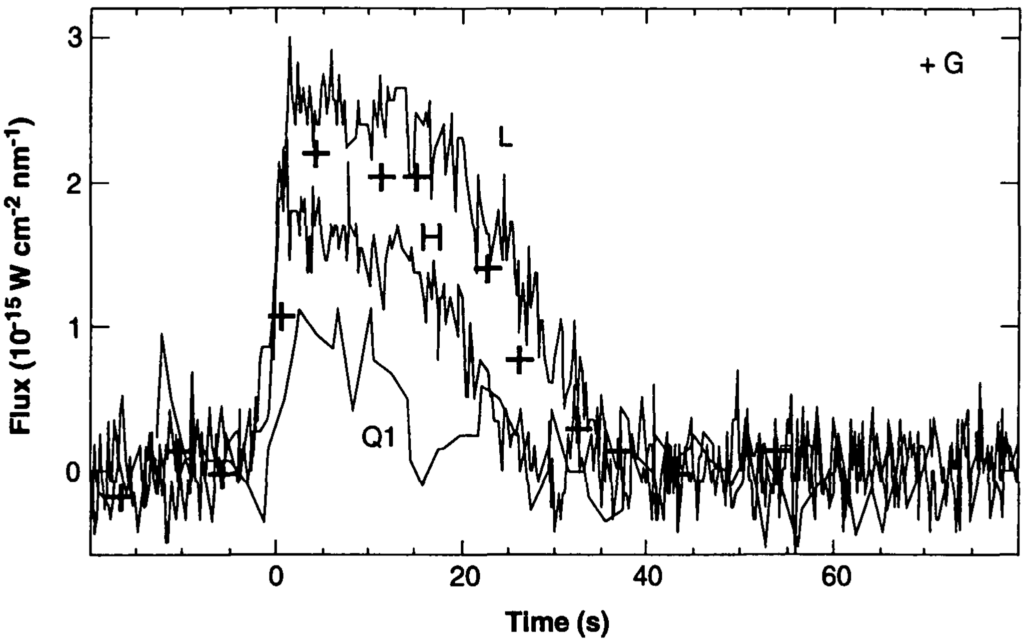

FIGURE 3. PPR light curves for L, H, Q1 (and G with lower sampling frequency), observed at 0.945 μm. (From Martin *et al.* 1995.)

away from any simple relationship between pre-impact inferred diameter and brightness of the bolide and early fireball phases.

PPR experimenters selected Q1 for observation in two wavelengths (in retrospect, we all wish that a brighter event had been observed this way). Data at the shorter wavelength (0.678 μm) show a sharp initial peak and more rapid decay than at the longer wavelength. A ratio of the two observations yields a color temperature of ~18,000 K, but because of the noise for this weak event and use of preliminary instrumental calibrations, the uncertainty in the derived temperature is at least a factor of 2.

The best characterized impact is for the G fragment, observed by three instruments simultaneously. UVS (0.292 μm) detected G at a time simultaneous with the rapid initial rise of the PPR light curve. The UVS signal of $(4.3\pm0.9)\times10^{-15}$ W cm^{-2} nm^{-1} compared with the PPR signal of $(1.1 \pm 0.2) \times 10^{-15}$ W cm^{-2} nm^{-1} allowed Hord *et al.* (1995) to calculate a color temperature of ~7800 ($\pm$600) K for that moment (probably early bolide phase). The assumption of black-body radiation is supported, to a degree, by the roughly black-body spectrum obtained for G by NIMS 5 s later. Hord *et al.* interpret their data to apply to bolide passage through the atmosphere. During the sample of data from the three instruments taken 5 s later, G is roughly 2 times brighter as observed by PPR at 0.945 μm; but it had dropped below detectability to the UVS, implying a temperature <5500 K. The subsequent fireball phase was also not detected by UVS, implying low temperatures, consistent with those derived from NIMS data (see below).

The subsequent development of the G impact has been beautifully characterized by NIMS data, operating in its "fixed map" mode (Carlson *et al.* 1995a). Observations were taken at 17 wavelengths between 0.7 and 5.0 μm. Signal above background (reflected sunlight from Jupiter at short wavelengths, jovian thermal radiation at 5 μm) was detected at 10 wavelengths between 1.8 and 4.4 μm; several wavelengths fall within deep jovian

Time After Impact, s	Temp., K	Fireball Diam. km.	Altitude km.	Source
0	7800	6	?	UVS/PPR
5	~5500	7	20	NIMS/UVS
10	3000	25	30	NIMS
20	2200	40	40	NIMS
35	1500	80	80	NIMS

TABLE 1. G Fireball Development

stratospheric methane absorption bands, while about 6 of them approximately define the black-body continuum.

NIMS sampled the impact phenomena once every ~5.3 s, as did PPR and UVS. However, due to spatial scanning by NIMS, the impact site was not observed by NIMS at exactly the same times as the PPR observations. The first NIMS detection was ~ 5 s after the first detection by PPR and UVS; the previous NIMS sample, perhaps 1 s before the PPR/UVS detection, showed nothing above background. The NIMS data are noisy, due to sensitivity variations within the detector, but the light curve at 4.4 μm (in the continuum) peaks about 40 s after first detection by PPR/UVS, about the same time that the PPR light curve has faded into the background. The luminosity at 4.4 μm fades to background about 75 s after onset. (The NIMS light curve for R, returned with half the sampling frequency, has the same character as for G, but is down in intensity by about a factor of 4 during the fireball phase.)

Luminosity is again detected by NIMS 6 min after onset for both G and R, as the splashback—best characterized by groundbased observations—begins. The 6 min interval observed by NIMS strongly confirms the inference from analysis of groundbased data (see Nicholson's review, this volume) that the interval represents a real physical attribute of the plumes, common to all the larger impacts, rather than an aspect of geometric visibility from Earth. NIMS data-return for G and R cease ~9 min after event onset, or 3 min into the splashback phase while the intensity is still increasing. (The intensity of the splashback phase for R is down by about a factor of 2 from that for G. More R data may be played back from the spacecraft during spring 1996.)

Besides contributing photometric observations at different wavelengths from those of PPR and UVS, NIMS provides two additional types of constraints to understanding the development of the G fireball. First, its series of simultaneous measurements at multiple continuum wavelengths *defines* the black-body temperature of the source; the multiple wavelengths demonstrate a roughly black-body emission, rather than requiring an *assumption* of black-body emission. Secondly, from the strength of the methane absorption bands (and several lesser absorbers that have been approximately modelled), Carlson *et al.* (1995a) can specify the effective altitude in Jupiter's atmosphere at which the emission takes place. As expected, the methane absorptions fade as fireball development progresses, indicating that the effective radiating surface of the fireball is rising in Jupiter's stratosphere.

Various preliminary interpretations of NIMS data (Carlson *et al.* 1995a; Spencer 1995) provide a self-consistent portrayal of an expanding, rising, cooling fireball during the first half-minute of NIMS observations of G. Table 1 summarizes (with approximate numbers) the development, beginning with UVS/PPR data on the bolide phase (for which there is no altitude estimate) and continuing with NIMS characterization of the fireball. The altitude of the top of the fireball is referenced to the top of the ammonia clouds, about 200 mb pressure, about 20 km below the tropopause.

The NIMS cartoon of the event is of the explosion occurring in the troposphere, just above cloudtop level, with the center of the resulting spherical fireball rising 1 km s^{-1} and the upper surface rising ~2 km s^{-1}, so that the bottom of the fireball remains near the cloud layer. Carlson *et al.* believe the NIMS data support an accelerating rise of the fireball, which would be the initial acceleration toward the >10 km s^{-1} velocities achieved by the plume. The cartoon is oversimplified, and it is not known whether the NIMS data pertain to the totality of the fireball or just to the part above the clouds (with much of the potentially luminous phenomena hidden beneath the opaque clouds). In all probability, however, it is this upper, most rapidly rising, part of the developing fireball that predominantly became the plume, whose expansion and later fallback was so well imaged by Hubble Space Telescope (Hammel *et al.* 1994) and whose thermal evolution was so spectacularly recorded by infrared telescopes on Earth.

Before the fireball phase faded below NIMS's detectability threshold more than a minute after impact, the temperature apparently fell to 1000 K; at about this time, the cooling plume became visible to Earth-based observers above the planet's limb and was detected (as the second precursor) at 2.3 μm; an HST image of the G fireball, apparently in emission, before rising into sunlight, was taken shortly afterwards.

3. Discussion

The *Galileo* data have played a fundamental role in reconciling what at first appeared to be very confusing Earth-based observations of the early stages of the impacts. While there was a chance that a few impacts would fall in occasional gaps in *Galileo*'s observational records, it appears that the major luminous event (at visible and near-IR wavelengths) was recorded for every impact for which *Galileo* data were returned to Earth: G, H, K, L, N, Q1, R, and W. In contrast to some pre-impact predictions, the impact events (as distinct from much later splashbacks) were singular rather than being characterized by separate flashes from the bolide and fireball phases. The preferred interpretation of Chapman *et al.* (1995a) was that the phases were combined, as the upper parts of the trail heated by the passing bolide exploded to become the upper portion of the fireball (as predicted by Boslough *et al.* 1994; see also Boslough *et al.* 1995).

However, prior to IAU Colloquium 156, a view was advanced at the ESO Workshop in Garching (Orton, 1995, and Drossart *et al.* 1995; also see Martin *et al.* 1995) that the *Galileo* data, including the initial spikes observed by SSI, correspond only to the fireball phase and that the bolide phase was so weak as to be invisible. At IAU Colloquium 156, Chapman *et al.* (1995b) argued against the "stealth bolide" model. As asserted above, the similar initial spikes in the data for such disparate impacts as K and N have timescales (a few seconds) appropriate for bolide entry and are unlikely to pertain to rapid fireball development. Moreover, the SSI data are quite sensitive. To have escaped detection during the observing periods, a stealth bolide would have to be <1% the maximum brightness of K and <0.5% the maximum brightness of the fainter W event (the detection threshold is better for W). Although terrestrial meteors have spectra dominated by line emission, there is expectation of considerable continuum radiation from these large jovian bolides (Chevalier & Sarazin, 1994; see discussion by Mac Low, this volume). It seems inconceivable that the bolides for K and W would not have been detected by SSI.

The Garching discussions clearly had been confused by a variety of Earth-based "precursor" detections of events from seconds to minutes prior to the *Galileo* flashes. Discussions at IAU Colloquium 156, assisted by presentation of more (and corrected) ground-

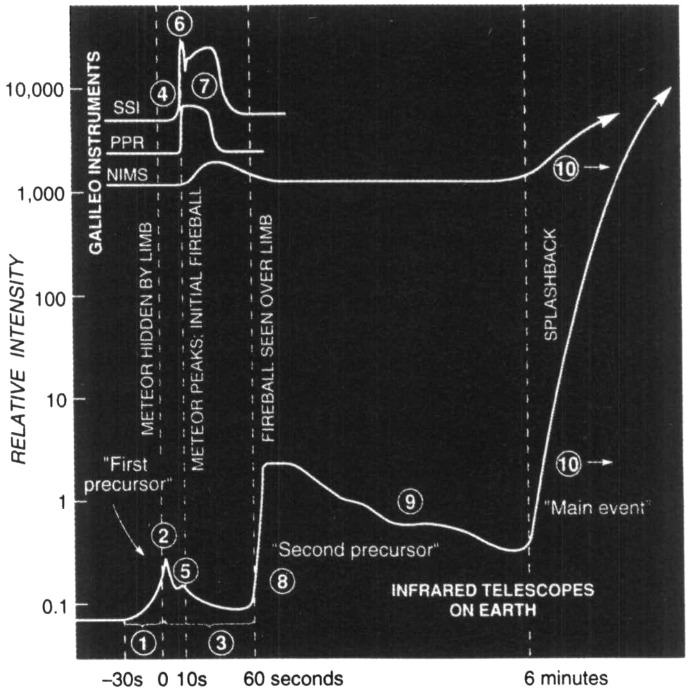

FIGURE 4. Schematic representation of a typical groundbased 2.3 μm SL9 light curve. Parts 1–3 are the first precursor. Shoulder (5) may be an indirect reflection of the sharp onset (4), initial bolide spike (6), and perhaps fireball phase (7) of the luminous phenomena observed directly by *Galileo* instruments. The second precursor (8, 9) and main splashback event (10) are also indicated; the latter was also detected by NIMS. Illustration developed during discussions at IAU Colloquium 156.

based data, clarified the situation, as shown in Fig. 4 (see Beatty and Levy, 1995). I now briefly summarize the chief elements of the synthesis. For more thorough discussion, especially for later stages of the light curves, see the review by Nicholson (this volume).

The initial rise of 2.3 μm groundbased light curves during the minute-or-so prior to the peak of the first precursor (#1 in Fig. 4, termed "leader emission" by Nicholson, this volume), seen for some events, varies considerably in different data sets, undoubtedly due to different sensitivities and time sampling intervals in addition to differences between the fragments and observing geometries. The most extreme reliable examples (*e.g.*, emission beginning ~3.5 min in advance of the commencement of the SSI K event, seen by McGregor *et al.* 1995) cannot possibly be attributed to the comet fragment in the upper atmosphere of Jupiter since the fragment was still >10,000 km from Jupiter at the time. If a very modest fraction of a fragment's mass were distributed in coma dust, it would produce a meteor storm as the dust grains reached nanobar pressures in Jupiter's upper atmosphere, in direct view from Earth (especially for later impacts). The time history of the leader emission presumably defines (mostly) the much-elongated trail of dust associated with the fragment, including the changing cross-section and volume density of the dust cloud along its length. Coma dust lagging behind the fragment might also contribute to the declining portion of the so-called first precursor spike.

The peak of the first precursor (#2, Fig. 4) is identified as the time that the fragment passes behind the limb, as seen from Earth. The first precursor may simply be the peak of the meteor storm, as the densest part of the coma (nearest the fragment) strikes Jupiter's uppermost atmosphere. The meteor storm luminosity may be augmented by initial luminosity of the fragment itself, during the few seconds before it passes behind the limb (see calculation by Mac Low, this volume). The smooth rise of the leader to the peak of the first precursor, with no jump in the few seconds before the peak (shown best in high time-resolution data, such as observed for L by Hamilton *et al.* 1995) argues that the first precursor is due to the meteor storm alone, with no required contribution from the fragment itself. Note that the observed brightnesses of the first precursors indicate that the phenomena would be below *Galileo*'s detection limit, for reasonable color temperatures. For impact K, SSI detected the event just 5 s prior to the peak of the initial spike.

The 10 s duration between first precursor and the peak of the initial spike of luminous phenomena observed by *Galileo* corresponds to the time-of-flight of a fragment from passage behind the limb down into Jupiter's stratosphere (cf. Sekanina, 1995). This interpretation is compatible with all first precursor data of which I am aware, taking into account different sampling frequencies, timing uncertainties, and the shorter time-of-flights for later impacts in the series.

Light curves of several first precursors suggest non-uniform decrease in brightness following the peaks (#3, Fig. 4), as well as a shallower rate of decrease than the smooth initial rises. The best defined light curve for a first precursor is that for L by Hamilton *et al.* (1995). It shows a suspension in the drop of the first precursor, a plateau, lasting for at least 8 s. The 2.3 μm luminosity observed during this period, particularly if the rapid discontinuities in the data are real, is most reasonably interpreted as some kind of indirect detection of the rapidly changing luminous events taking place far below Jupiter's limb during the last phases of bolide entry and early fireball development (the "explosion"). The end of the plateau (#5, Fig. 4) may correspond to the brightest phase of the luminous phenomena in Jupiter's upper troposphere—the bolide and its explosive conversion into the initial fireball. Back-of-the-envelope calculations suggest that a plausible amount of comet dust deposited at high elevations during the meteor storm could conceivably reflect efficiently enough to account for the observations, but more analysis is needed.

As many researchers have commented, the second precursor observed from the Earth (#8, Fig. 4), occurring about a minute after impact (earlier for the later impacts), is readily interpreted as the fireball/plume rising into view from Earth above Jupiter's limb (and, for the shortest wavelength observations, by subsequent rise into sunlight). *Galileo* SSI detection of K at 0.89 μm fades out just as groundbased observers (*e.g.*, Watanabe *et al.* 1995) detected the onset of the second precursor. Preliminary studies of SSI imaging of K fail to show the sun-illuminated plume; calculations (Chapman and Merline, in preparation) suggest that it would be near the detection threshold. Six minutes after impact, re-impact of high velocity plume material generates the beginning of the main splashback thermal event (#10, Fig. 4).

4. Conclusions

The *Galileo* data define the early luminous phases of SL9 impacts, beginning with bolide penetration into Jupiter's atmosphere (but a few seconds after the groundbased first precursors, which are apparently due to a meteor storm at nanobar pressure levels) continuing through the period when a rising, expanding, cooling fireball was beginning to be directly visible from Earth. For the brightest events, the bolide and early (first 20 s) fireball luminosities were equal, indicating a continuity of the physical evolution of the hot bolide train into the upper part of the fireball. Perhaps a much brighter explosion occurred at depth in Jupiter's atmosphere, but its luminosity would have been hidden below the clouds. The portion of the superheated column of atmosphere above the clouds evidently developed into the upper, visible part of the fireball that evolved into the plume, later observed by HST and groundbased observers.

Smaller events (including those, like N, that evidently developed minor plumes/splash-backs and small dark spots) had bolides only slightly fainter than the largest impacts, but the fireball luminosities were much fainter. The "duds" or "fizzles" may have been clouds of dust without major fragments, or the fragments may simply have been below the threshold size required to produce a plume and splashback; from the Earth, fragment V (Nicholson, this volume) exhibits a classic first precursor light curve, but the *Galileo* SSI data—which might show a bolide spike, if a main fragment accompanied the dust—have not been returned to Earth and will soon be overwritten.

It is noteworthy that a wide variety of impacts, ranging from the mightiest (L) to one of the weakest non-fizzles (N) all have peak bolide-phase brightnesses within a factor of 5. Possibly this could imply that widely different size impactors give rise to similar bolide flashes (meteor physics for such large objects is not well understood). More likely, the sizes of most of the SL9 fragments ranged within roughly a factor of 2, despite larger differences inferred from pre-impact estimates and, especially, from extraordinary variations in the late-stage phenomena observed from Earth. It might, indeed, be regarded as fortuitous that the fragment sizes would thus seem to be near the threshold size capable of generating large dark splotches in Jupiter's upper atmosphere.

Equally noteworthy was the faintness of the luminosity from both the bolide and fireball phases. Mac Low (this volume) interprets both as evidence for small ($\sim$0.5 km diameter) fragment sizes, confirming the robust calculations from the physics of tidal break-up (cf. Asphaug and Benz, 1996). The apparent lack of SL9-like dark spots on Jupiter's face during the past century of nearly continuous observations by amateur and professional astronomers thus may be a constraint on the number of comets $>$0.5 km diameter encountering Jupiter during the present epoch.

The *Galileo* results reported here are based on only a fraction of what will eventually be learned from complete reduction and interpretation of the data bases. With the *Galileo* orbiter now observing the Galilean satellites, the *Galileo* Science Team is necessarily deeply engaged in the intensive multiple-encounter activities. But eventually additional SL9 data will be analyzed, calibrations improved, and further insights about this remarkable astronomical event will emerge.

This research was supported by the *Galileo* Project and by grants from the National Science Foundation and NASA. I thank *Galileo* Project personnel for the extra work that made these observations possible. I thank Torrence Johnson and especially W. Merline for discussions.

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