The orbital motion and impact circumstances of Comet Shoemaker-Levy 9

By PAUL W. CHODAS and DONALD K. YEOMANS

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

Two months after the discovery of comet Shoemaker-Levy 9 came the astonishing announcement that the comet would impact Jupiter in July 1994. Computing the orbital motion of this remarkable comet presented several unusual challenges. We review the pre-impact orbit computations and impact predictions for SL9, from the preliminary orbit solutions shortly after discovery to the final set of predictions before the impacts. The final set of predicted impact times were systematically early by an average of 7 minutes, probably due to systematic errors in the reference star catalogs used in the reduction of the fragments' astrometric positions. The actual impact times were inferred from the times of observed phenomena for 16 of the impacts. Orbit solutions for the fragments were refined by using the actual impact times as additional data, and by estimating and removing measurement biases from the astrometric observations. The final orbit solutions for 21 fragments are tabulated, along with final estimates of the impact times and locations. The pre-breakup orbital history of the comet was investigated statistically, via a Monte Carlo analysis. The progenitor nucleus of SL9 was most likely captured by Jupiter around 1929 $\pm$ 9 years. Prior to capture, the comet was in a low-eccentricity, low-inclination heliocentric orbit entirely inside Jupiter's orbit, or, less likely, entirely outside. The ensemble of possible pre-capture orbits is consistent with a group of Jupiter family comets known as the quasi-Hildas.

1. Introduction

The late-March 1993 discovery of multiple comet Shoemaker-Levy 9 by Carolyn and Gene Shoemaker and David Levy set in motion an extraordinary international effort to study the evolution of a remarkable cometary phenomenon and to witness its ultimate collision with Jupiter (Shoemaker *et al.* 1993). From the beginning, it was clear that the orbital dynamics of this comet were unique. It had spectacularly split into $\sim$ 20 fragments, most likely because of tidal disruption during a recent very close approach to Jupiter. Preliminary orbit computations soon confirmed the close approach, and revealed the surprising fact that the comet was actually in orbit about the planet (Marsden 1993b). Even more extraordinary news came several weeks later, when further orbit computations suggested that the comet would likely collide with Jupiter in late July 1994 (Nakano 1993, Yeomans and Chodas 1993a). Early calculations indicated that the collision would take place on the far side of the planet as viewed from the Earth, but the precise location was very uncertain. After the comet emerged from solar conjunction in December 1993, important new astrometric measurements were added to the data set, and the predicted impact locations moved much closer to the limb of Jupiter, although they were still on the far side (Yeomans and Chodas 1993d). During the months leading up to the impacts, increasingly more accurate predictions of the impact times and locations were computed and distributed electronically to the astronomical community. These predictions made it possible for the extraordinary impact events to be well recorded by an unprecedented array of ground-based and space-based instruments.

Orbital computations for comet Shoemaker-Levy 9 (referred to as SL9 hereafter) presented several challenges beyond what is normally the case for comets and asteroids.

Because the comet was in orbit about Jupiter and was heading for an impact, new parameters such as jovicentric positions and velocities in various reference frames, jovicentric orbital elements, impact times, and impact locations had to be computed. Since the comet had fragmented into a string of nuclei with no obvious bright central condensation to use as a reference point, astrometric measurements and orbit computations were referenced to the mid-point of the string, which was rather ill-defined. Eventually, the mid-point was abandoned in favor of tracking the approximately 20 individual fragments, requiring that orbit computations and impact predictions be repeated for each nucleus. Determining the orbits for some of the fainter fragments was difficult, since very little astrometric data were available for these poorly observed objects. Some of the fragments disappeared completely as the comet evolved, while others split. Proper identification of fragments was a problem, as they were sometimes mislabeled in the astrometric data. Detective work was required to sort out their true identities. Even Mother Nature conspired to add confusion, when a telescope observing SL9 from Kitt Peak in Arizona was unknowingly shaken during the January 17, 1994 earthquake in southern California. The effect of the earthquake on these astrometric observations was detected only through the resulting large orbit residuals.

Accurately determining the motion of the fragments close to the July 1994 impacts offered additional computational challenges. The need for accurate impact predictions required the modeling of the perturbative effects of the Galilean satellites and Jupiter's oblateness. Also, as the fragments approached the planet, their motion became very non-linear. The fact that our software used a variable integration step size, and that the partial derivatives required in the orbital differential correction process were numerically integrated along with the comet's motion, rather than being approximated using finite differences, allowed us to refine the orbit solutions right up to the times of impact.

In the next section, we review the pre-impact orbit computations and impact predictions for SL9, from the preliminary orbit solutions shortly after discovery to the final set of predictions before the impacts. We then discuss post-impact analyses, indicating how the observed impact phenomena were interpreted, and how the actual impact times were inferred. We give a compilation of the times of key events in the observed light curves. Following this, we describe how the orbit solutions were improved after the impacts, by using the actual impact times as additional data, and by removing measurement biases from the astrometric observations. We tabulate our final orbit solutions for 21 fragments, in both heliocentric and jovicentric forms. Next, we present our final estimates of the impact times, locations, and geometries, as derived from the final orbit solutions. Finally, we discuss the pre-breakup orbital history of the comet, which we have investigated statistically using a Monte Carlo analysis. We give our estimate of when the comet was likely captured by Jupiter, and characterize SL9's possible pre-capture heliocentric orbits.

2. Pre-impact orbital analyses and impact predictions

The early orbital analyses of SL9 were based on the supposition that the comet had broken up during a recent close approach to Jupiter. The circumstantial evidence was strong: SL9 had split into a large number of fragments in a well organized geometry, and it was currently situated only 4 degrees from the largest planet in the Solar System. Tidal disruption during an approach to within the Roche limit of a large perturbing body is a common mechanism for cometary splitting. Several comets have been known to split after close approaches to the Sun, and one, P/Brooks 2, is known to have split after approaching Jupiter to ~ 2 Jupiter radii (R_J) in July, 1886 (Sekanina and Yeomans

1985). Thus, the supposed breakup scenario would not be unprecedented. It was far from a certainty, however, as comets have been seen to split spontaneously, when nowhere near a large body. The day after the announcement of the comet's discovery, B. G. Marsden published a very preliminary orbit solution in which he used the assumption of a close passage by Jupiter (Marsden 1993a). His computations suggested that the comet's close approach to the planet had been at a distance of 0.04 AU in late July 1992, surprisingly accurate considering how little data were used in the solution. It would be many weeks before enough astrometric data became available to confirm that the comet had indeed made an extremely close approach to Jupiter on July 7, 1992, at a distance of only 1.3 R_J from the center of the planet.

Computing the orbit of SL9 in the first month or so after its discovery was very difficult. Few astrometric measurements were available, and the presence of nearby Jupiter introduced a large nonlinearity into the orbit computations. Furthermore, SL9 had no single central condensation to serve as a reference point for astrometric measurements. Since the individual nuclei were not easily resolvable by many observers, the convention was adopted to measure only the center of the train of nuclei, the mid-point of the bar (Marsden 1993b). This simplifying assumption greatly facilitated astrometry for many observers, especially amateurs, who provided a large fraction of the early measurements. We certainly would not have learned as much as we did about the orbit of SL9 as quickly as we did without this convention. However, the center of the train was rather ill-defined, and different observers placed it at different points in the train, according to the extent of the train each could see. Moreover, as the length of the train grew, errors in locating its center also grew.

A week after his first orbit solution, Marsden (1993b) obtained an improved solution which indicated a surprising new result: SL9 appeared to be in orbit about Jupiter. This was also not unprecedented. Carusi *et al.* (1985) investigated the long-term motion of all periodic comets with well-known orbits and found several that had either been in temporary Jupiter orbit in the past, or would enter temporary orbit in the relatively near future. Tancredi *et al.* (1990) investigated the temporary capture of comet P/Helin-Roman-Crockett by Jupiter during intervals centered on close approaches to Jupiter in 1976 and 2075. Using more recent orbit solutions, with nongravitational effects included when appropriate, we studied the motions of seven comets other than SL9 that either have been, or will be, temporary satellites of Jupiter (Yeomans and Chodas 1994b).

By early May, the span of astrometric observations was sufficiently long to begin to reveal the true collision trajectory of the comet. Amateur observers had contributed a large number of valuable measurements, and as more and more of these were used, orbital computations by S. Nakano and Marsden began to indicate the possibility of impact in July 1994. Now, this was truly unprecedented. Marsden alerted us of this exciting development on May 21, and provided the key set of recent astrometric measurements. We immediately confirmed Nakano and Marsden's computations, and computed that the probability of impact was about 50%. Our software had just recently been augmented with the capability to estimate probability of impact, in preparation for a study of the hazards of near-Earth objects (Chodas 1993; Yeomans and Chodas 1995). The dramatic announcement of the impending collision was issued the next day (Marsden 1993c), along with Nakano's orbit solution (Nakano 1993). One of our initial orbit solutions appeared in the Minor Planet Circulars shortly after (Yeomans and Chodas 1993b). Within a few days of the impact announcement, as more astrometric data became available, the probability of impact rose to 64% (Yeomans and Chodas 1993a), and it reached 95% only a week later.

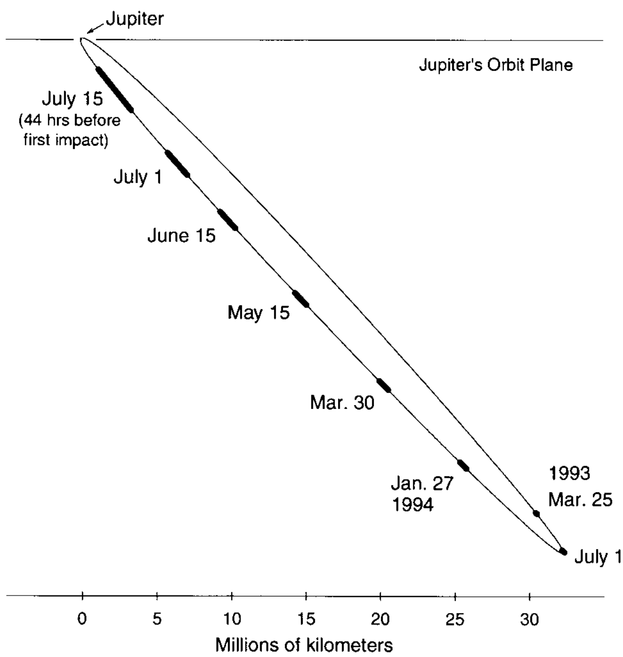

FIGURE 1. The orbit of comet Shoemaker-Levy 9 about Jupiter, as viewed from the direction of Earth on May 15, 1994. The length and orientation of the train of fragments are shown to scale on eight dates. The train is nearly aligned along the velocity vector, except near apojove. The orbit is somewhat foreshortened in this view; the major axis rises out of the plane of the diagram towards the viewer at an angle of about 20 degrees.

To determine the basic characteristics of SL9's orbit and its impending impact, we quickly modified our software to provide jovicentric information, including position, velocity, and orbital elements as a function of time. It became clear that the comet was approaching the apojove of an extremely eccentric orbit about Jupiter, with eccentricity ~ 0.99 and apojove distance ~ 0.33 AU (see Fig. 1). By June 1, we had determined that the impact would occur in the mid-southern latitudes of Jupiter, and, unfortunately, on the side of the planet facing away from Earth. We defined impact to occur when the comet reached the one bar pressure level in Jupiter's atmosphere, which we modeled as an oblate spheroid with radius and flattening given by Davies *et al.* (1992). Finding the moment of impact in these early solutions required searching through tables of numbers, but we soon automated this important function. We also wrote software to compute and plot the motion of the comet in various jovicentric frames, which helped in visualizing its trajectory (Yeomans and Chodas 1993c). With it, we determined that the Galileo spacecraft would likely have a direct view of the impact, although this was far from certain because the predicted impact was right on the limb.

There was much more to study with this dynamically fascinating object. For one thing, it had a whole train of nuclei to consider. As SL9 passed through apojove around July 13, the question arose as to whether the fragments would reverse their order on the sky as viewed from the Earth. After all, they had 'turned the corner' and were heading back to Jupiter. But in fact, the appearance of the train did not change because the fragments were not all on the same orbit. A useful analogy is to think of throwing a handful of pebbles upwards, each receiving a slightly different vertical velocity. The slowest pebble trails the others going upwards, but it reaches its apex first and is the first to hit the ground; furthermore, the separations between the pebbles increase monotonically during their flight. With SL9, the eastern-most fragment trailed the others on the outbound leg, reached apojove first, and became the leading fragment inbound. The fragments passed through apojoves in sequence over a period of a few days, while the train continued its expansion and remained approximately pointed at Jupiter throughout.

As SL9 headed into solar conjunction in late July, other important questions were being raised. Would all the fragments collide with Jupiter? Would any of them impact on the side of Jupiter visible from Earth? Unfortunately, no astrometric measurements of individual nuclei were available for computing orbit solutions. In anticipation of their availability, however, we wrote new software to investigate how slight variations in an object's orbit at one epoch would affect its position on the plane of sky at later epochs. We would soon use this software to study the tidal splitting of the comet and explain the appearance of the train. Scotti and Melosh (1993) used a similar model when, armed with Scotti's measurements of the train length and orientation, they determined that the progenitor nucleus needed to be only 1 km in radius to explain the observed train dimensions, assuming disruption occurred at perijove. They also determined that the entire train would impact Jupiter over a period of 5.6 days. With Scotti's train measurements in hand, and using their assumptions, we confirmed these results and furthermore determined that all the fragments would impact Jupiter on the far side as viewed from Earth.

The first astrometric measurements of individual nuclei became available in October 1993. These were positions of 21 fragments obtained by Jewitt *et al.* (1993) on four nights from March through July, 1993. The positions were offsets from the brightest nucleus, designated 7 in Jewitt's numbering system. In collaboration with Z. Sekanina, we determined the effective time of tidal disruption and the impulse each fragment must have received in order to appear at the observed relative positions. This approach provided the first orbital solutions and predicted impact times for individual fragments, which we denoted A through W (Chodas and Yeomans 1993). Because the relative times were known much better than the absolute times, these first impact time predictions were given relative to the impact time of the center of the train. The relative times all turned out to be within 40 minutes of the actual impact times relative to the center time, remarkable precision considering the prediction for each fragment was based on only 4 measurements taken over a year before impact. This accuracy attests to the precision of Jewitt *et al.*'s measurements, and indicates the great utility of the tidal disruption approach for computing orbit solutions. Our orbit solutions indicated that, to match the observed position angle history of the train at the 0.1 degree level, the effective time of tidal breakup of the progenitor comet had to be $\sim$ 2.2 hr after perijove passage in 1992. From this and other evidence, we concluded that the radius of the progenitor comet was probably $\sim$ 5 km. (Sekanina *et al.* 1994).

Other important predictions required at this time included the expected uncertainties of the predicted impact times in the last weeks and days before impact. The impact time accuracy was required to plan impact observations, especially those to be made by spacecraft, which had to programmed well in advance of the event. The rate of decrease of the impact time uncertainty depended upon the number of the astrometric measurements used in the orbit solutions, as well as their quality. Assuming a conservative 9 measurements per month and a 1-arcsec measurement accuracy, we estimated the 1-sigma impact time uncertainty a month before impact would be $\sim$ 13 minutes, and a week before impact, $\sim$ 7 minutes. If only two more measurements could be made on the two days before impact, the uncertainty would drop to $\sim$ 3 minutes. Clearly, the most powerful observations for determining impact times were those closest to impact. But how close to bright Jupiter could the faint cometary fragments be observed?

In November, the first batches of absolute astrometric measurements for individual fragments became available: J. V. Scotti and T. Metcalfe provided 250 measurements obtained from Kitt Peak over the period March through July, and A. Whipple and P. Shelus provided 54 measurements obtained from McDonald Observatory taken in April and May. Marsden (1993d) used the Kitt Peak data to compute the first independent orbit solutions for individual fragments (*i.e.,* solutions which made no assumptions about the tidal disruption process), and we used both observation sets in similar solutions a few days later. Only the nine brightest fragments (E, G, H, K, L, Q, R, S, and W) had enough astrometric data to yield well-determined solutions. The impact times derived from these solutions were about 18 hours earlier than those based on the center-of-train solution and relative astrometry. This jump was most likely due to errors in locating the center of the train: the east end of the train may have been too faint to be seen by many of the observers. The new orbit solutions superceded the center-of-train solutions, which were now abandoned; astrometry and orbit computations from this time onwards referred only to individual fragments. The impact time uncertainties actually increased slightly with the new solutions, because the fragments had fewer measurements than the center-of-train orbits, but at least the solutions were now tied to well-defined points.

The emergence of SL9 from solar conjunction was greatly anticipated. Although attention focused on possible changes in the appearance of the comet, we were anxious because new astrometric data would dramatically improve the orbit solutions. On December 9, sooner than expected, Scotti recovered the comet. Although the train had lengthened, the fragments appeared much the same as before conjunction. Marsden (1993e) computed new orbit solutions for the nine brightest fragments and found that the impact times were almost a day earlier than in previous solutions. We confirmed Marsden's computations, and found an exciting new result: the predicted impact locations, though still on the far side of Jupiter, were now much closer to the morning terminator, only 5–10 degrees behind the limb as seen from the Earth, with the later impacts closest to the limb (Yeomans and Chodas 1993d, Chodas and Yeomans 1994a). The impact sites had also moved well onto the hemisphere visible to Galileo. Would the predicted impact locations continue to move towards the limb, and possibly even onto the near side? Unfortunately not. These would be the last large changes in the predictions, because the orbit solutions had become relatively well determined. Based on Monte Carlo analyses which used actual orbit uncertainties and correlations, we concluded that there was little chance that any of the fragments would impact the side of Jupiter visible to the Earth.

In mid-December, our impact predictions, together with orbital elements and ephemerides for the nine brightest fragments, were posted on the special SL9 electronic bulletin board operated at the Planetary Data Systems' Small Bodies Node at the University of Maryland (UMD). Over the remaining seven months before impact, we posted over a dozen more sets of predictions, and associated data. The predicted parameters in our tables included impact time, jovicentric latitude, meridian angle, and the Earth-Jupiter-fragment (E-J-F) angle at impact. This latter angle indicated how far behind the limb the impact would occur. The meridian angle was defined as the jovicentric longitude of impact relative to the midnight meridian, measured towards the morning terminator. This relative longitude was known much more accurately than the Jupiter-fixed longitude, because of the large uncertainty in the impact times and Jupiter's fast rotation. Basically, the approach trajectory of each fragment was known much more accurately than the fragment's location on that trajectory at any given time. Predictions of absolute jovicentric longitude were not included in our tables until later, when the

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impact times were better known. Also added later were predictions of satellite longitudes at impact for four of the inner jovian satellites, Amalthea, Io, Europa, and Ganymede, kindly supplied by P. D. Nicholson.

Keeping track of all the fragments was a continual challenge. Not only were there a lot of them to consider, but each seemed to have its own personality. In January 1994, only seven fragments (G, H, K, L, Q, S, and W) had well-established orbit solutions and consistent impact predictions, while solutions for E and R remained a little erratic, as they were based on fewer measurements. The rest of the fragments had too little astrometric data to determine reliable independent orbit solutions, so we applied our tidal disruption model as we had done earlier, although now we varied the orbit of fragment Q instead of the orbit for the center of the train. By the end of the month, as more observations became available, the solutions for fragments E and R became consistent with the rest, and fragment F graduated to the group with independent solutions. The image of SL9 taken by the Hubble Space Telescope (HST) in late January revealed changes in the SL9 menagerie: fragments J and M had disappeared completely, and fragments in the P–Q region had clearly split. For a time, there was confusion in identifying fragments in this region, with N identified as P and the P sub-fragments identified as Q3 and Q4, but by mid-February the P1/P2 and Q1/Q2 nomenclature was established (Marsden 1994a). Correctly identifying the fainter fragments in ground-based observations was a recurring problem, as the fragments were often near the limits of detectability. We checked observer's identifications by comparing observations against positions predicted from orbit solutions, but this was an imperfect process because the orbit solutions for these faint fragments were not well-determined either.

By late February, independent orbit solutions had been computed for 19 fragments by both Marsden (1994b) and ourselves, although only 12 fragments (the original nine, plus F, N, and P2) had solutions reliable enough to be used in our impact predictions (Chodas *et al.* 1994). By early June we had adopted independent orbit solutions for all fragments but Q2, although the impact predictions for the extremely faint fragments T and U continued to be erratic for several more weeks. Fragment Q2 was especially difficult, as it had very few measurements. Using HST measurements of the offset of Q2 from Q1, Sekanina (1995) applied our disruption model to determine that Q2 likely broke away from Q1 in the March–April 1993 period, right around the time of discovery of SL9. Not until July did the separation between Q1 and Q2 increase to the point that many ground-based observers could resolve the two fragments; we finally adopted an independent solution for Q2 in the last set of predictions before its impact.

In April, we upgraded the dynamical models used in our orbit determinations and impact predictions. Up until this time, we had used only point mass perturbations by the sun and planets, with planetary positions and masses taken from JPL planetary ephemeris DE200 (Standish 1990). But now, we switched to the more accurate planetary ephemeris DE245, and refined our models to include perturbations due to the Galilean satellites and the J2 and J4 zonal harmonic terms of Jupiter's gravity field. The positions of the Galilean satellites were computed using the analytic theory by Lieske (1977, 1994), while the parameters for Jupiter's gravity field were obtained from Campbell and Synnott (1985). Since the SL9 fragments approached Jupiter from the south, and impacted in the southern hemisphere, they did not come near the Galilean satellites on their final approach, and, as a result, the inclusion of the satellite perturbations had only a minor effect on the impact times. Similarly, the inclusion of the Jupiter oblateness perturbations made only a small difference in the predicted impact times. Both perturbations, however, were important in the long term backward integration of the comet's motion, discussed in section 6.

As SL9 passed through opposition in the April–May 1994 period, the number of astrometric observations increased dramatically, and the measurements themselves became more powerful in reducing orbital uncertainties, simply because the Earth was closer to the comet. During this time, the predictions drifted towards later impact times for most fragments, until, at the end of May, they were about an hour later than they had been in March. Meanwhile, the formal impact time uncertainties fell from about 30 minutes to 18 minutes (1-sigma), for the brightest fragments. The drift in impact times reversed itself in June and early July, with times sliding earlier by 30–50 minutes on average, while the impact time uncertainties fell to less than 10 minutes. The relatively large shifts in predicted impact times were a concern in the period from mid-June to early July, as final predictions had to be made for use in the Galileo impact observation sequences. The spacecraft was programmed to observe during a window of only 20–60 minutes around each of the predicted times. As it turned out, of the 16 impacts observed by Galileo instruments, only one was missed because the event shifted out of the observing window.

The most likely explanation for the large shifts in the predicted impact times was the presence of systematic errors in the reference star catalogs used by observers in reducing their measurements. Star catalog errors can be a major error source for precision orbit determination of comets and asteroids. Since background stars in an astrometric image are used as reference points in determining the position of an object of interest, systematic errors in the tabulated coordinates and proper motions of the reference stars lead to systematic errors in the deduced positions for the object. Most of the astrometric data for SL9 were reduced with respect to versions 1.1 or 1.2 of the *Hubble Space Telescope Guide Star Catalog* (GSC), which contains systematic errors of $\sim$ 0.5 arcsec for some regions of the sky. These errors are significantly larger than the typical errors incurred in actually measuring the position of the nucleus in the image, which could be as small as $\sim$ 0.2 arcsec in the best ground-based observations. In our orbit solutions, we modeled measurement errors simply as zero-mean Gaussian noise, and used a standard deviation, or noise value, of 1 arcsec for most observations, to account for the star catalog errors.

Since the most powerful astrometric data for reducing uncertainties in the predicted impact times would be those data taken closest to impact, it was especially important to try to reduce systematic star catalog errors in the region occupied by the comet near impact. To this end, J. V. Scotti generated and distributed a special reference star catalog for the region traversed by the comet in the last week before impact. Scotti made offset corrections to GSC reference stars by differencing the positions of stars common to the GSC and the more accurate PPM catalog (Roeser and Bastian 1989). Observations reduced with respect to Scotii's special catalog were assigned a noise value of 0.6 arcsec in our solutions.

A pre-publication version of the Hipparcos star catalog, kindly provided by M. Perryman and C. Turon of the Hipparcos project, was used by R. West and O. Hainaut in the reduction of a number of observations from the European Southern Observatory (ESO) taken between May 1 and July 14, 1994. Because the Hipparcos catalog is known to be highly accurate, systematic star catalog errors should be largely absent from these measurements, and we therefore assigned them noise values of 0.3 arcsec in our solutions. The post-fit root-mean-square (rms) of the ESO observation residuals was about one third the size of the rms of all the residuals.

The ESO group was able to obtain astrometric images close to Jupiter, with enough sensitivity to see even the fainter fragments. Theirs were the last astrometric observations taken of eight of the faintest fragments, ranging from 2.3 to 7 days before impact. Several other groups attempted to observe the SL9 fragments even closer to impact by using coronographs to block out the light from Jupiter, but this proved to be a very difficult task. Only two groups succeeded in obtaining astrometric data using this approach: D. Rabinowitz and H. Butner at Las Campanas obtained the last astrometric observations of fragments E, G, and L, with E seen only 1.45 days before its impact, and D. Jewitt and D. Tholen on Mauna Kea obtained the last astrometry for fragments P2, Q2, Q1, R, and S, with P2 caught only 1.33 days before its impact. Observations of several fragments even closer to impact were made by the Hubble Space Telescope, but these did not provide astrometry, except for a measurement of Q2 relative to Q1 within 10 hours of the Q2 impact.

Our final set of predicted impact parameters was issued on the UMD e-mail exploder only 4 hours before impact A. The impact time uncertainties were down in the 3–5 minute range (1-sigma) for most of the fragments, not much different from our original projection of 3 minutes made nine months earlier. Although for most of the fragments, observers had not been able to obtain astrometry as close to impact as we had hoped, they had contributed many more measurements than we had anticipated—about 3200 in total, spread over 20 fragments. Extensive and accurate astrometric data had been received from several observatories, including Catalina Station, Kavalur, Klet, Kuma Kogen, La Palma, La Silla, Mauna Kea, McDonald, Siding Spring, Steward, and the U.S. Naval Observatory at Flagstaff. The highly-accurate Hipparcos-based astrometry was also unanticipated, and it contributed greatly to the accuracy of the orbital solutions.

3. Estimates of impact times from observed phenomena

During and after impact week, our attention turned to the problem of determining the actual impact times, based on the timing of observed impact phenomena. This was especially important for maximizing the data return from the Galileo spacecraft, which had viewed the impacts directly. Because of difficulties with its main antenna, the spacecraft had recorded most of its impact observations on tape, and could replay only a small fraction of the data back to Earth. Accurate impact time estimates would help to quickly locate the portions of data obtained around the times of the impacts. Fortunately, observers using Earth-based telescopes and the HST had detected a variety of impact phenomena, and promptly made the times available on the e-mail exploder.

After the first few impact events, it became clear that our predicted impact times were systematically early by 5–10 minutes. This conclusion was based on the assumption that the impacts occurred around the times of the earliest phenomena for each event. Although various types of impact observations were reported, the most robust and consistent set were the phenomena seen in the near-infrared and mid-infrared wavelengths. These light curves followed a consistent pattern, starting with a *precursor* flash, and sometimes even two, followed ~ 6 minutes later by the start of a dramatic brightening which later became known as the *main event*. This surprisingly bright feature peaked about 10 minutes after the precursor (see the chapter by Nicholson for details).

The interpretation of the IR light curve features was initially puzzling, with the unusual viewing geometry complicating an already poorly-understood process. The limb of Jupiter just barely occulted the impact sites, and Jupiter's rotation brought them into full view anywhere from 20 minutes later for impact A, to 10 minutes later for W. The precursor was generally believed to be associated with the impact itself, but whether it was the meteor phase being observed directly, or an indirect view of the impact explosion reflected off incoming cometary debris, was not clear. Based on our predictions of how far behind the limb the impacts occurred, the meteors would have to be very high in Jupiter's atmosphere to be visible from Earth, especially for the earlier impacts. The interpretation of the main event was also uncertain. It could not be the plume rising above the limb of the planet, or the plume emerging into sunlight, because models suggested this would occur only a minute or two after impact (Boslough *et al.* 1994). Another possibility was that the main event was simply the impact site rotating into view, but then there should have been a variation in the time between precursor and main event, according to how far behind the limb the impact occurred.

Confirmation that the IR precursors occurred near the time of impact came from photometric observations obtained by the Photopolarimeter Radiometer (PPR) instrument on board Galileo. Transmitted to Earth within a day of the events, the PPR light curves of the H and L impacts displayed a 2-second rise to peak, followed by a plateau and slow decrease, lasting a total of 25–35 s (Martin *et al.* 1995). The sharp rise was interpreted as corresponding to the final moments of the bolide's trajectory, while the plateau and decay were due to the subsequent expanding and cooling fireball. The times of the initial PPR detection of the H and L impacts matched the times of precursors flashes to within a minute or so, although most of the reported flashes followed the PPR start times by about 1 minute. The PPR times also provided the first accurate calibration of our predicted impact times. The predictions for H and L were an average of 7 minutes early, an effect we subsequently concluded was due to systematic errors in the star catalogs.

Shortly after the impacts ended, we compiled our best estimates of the actual impact times, based on the reported times of various observed phenomena (Yeomans and Chodas 1994a). For impacts H and L, we simply adopted the times of initial detection in the PPR data. For the majority of the other impacts, which had consistent reports of precursor flashes and main events starting 5–6 minutes later, we generally took the impact time to be one minute before the flash time, or $\sim$ 6 minutes before the main event start. We also considered a set of impact times determined from measurements of the longitudes of impact spots seen in HST images (Hammel *et al.* 1995). The measured longitudes were differenced with predicted longitudes, converted to time differences by dividing by the rotation rate of Jupiter, and added onto the predicted impact times. These times could only be used as guides, however, as they seemed to be uncertain by 3–4 minutes. Finally, for fragments with no observed impact phenomena, we simply added an empirical correction of 7 minutes to the predicted impact times (Chodas and Yeomans 1994b).

The estimates of the actual impact times were used to position the Galileo tape for playback of selected portions of the data during the period from August 1994 through February 1995. Images of impacts K, N, and W taken by the Solid State Imager (SSI) were successfully returned, as were time series of spectra for impacts G and R taken by the Near-Infrared Mapping Spectrometer (NIMS) and Ultraviolet Spectrometer (UVS), as well as a PPR light curve for impact G. The Galileo data yielded accurate impact times for a total of 8 impacts: G, H, K, L, N, Q1, R, and W. The new impact time data confirmed our conclusion that the impact predictions were $\sim$ 7 minutes early.

The NIMS light curves for both G and R showed two phases—a fireball phase, due to the hot, expanding plume formed from the impact explosion, and a splash phase attributed to plume material falling back onto the atmosphere, heating it and producing thermal emission. For both the G and R events, the splash phase started $\sim$ 360 seconds after impact, and continued increasing for several minutes, through the end of the data sets (Carlson *et al.* 1995b). The delay between impact and onset of the splash phase seemed to be an intrinsic property of the impacts. Furthermore, it matched the 6 minute delay between first precursor and main event start seen in ground-based IR light curves of all the well-observed impacts, suggesting that the onset of the main event was not controlled by observing geometry, and the region of atmospheric heating was directly observable from Earth for most, if not all, the impacts (Zahnle and MacLow 1995).