Frequently Asked Questions about the
Collision of Comet Shoemaker−Levy 9 with Jupiter

Post−Impact Questions and Answers
Last Updated on November 10, 1994

This is a continuation of the pre−impact FAQ list which contains information about the comet's discovery, orbit, tidal breakup, and fragment sizes. The answers to questions Q3.2 to Q3.6 below were provided by Mark Boslough and David Crawford. Send additions, corrections or comments to astro@tamu.edu. A text version of this FAQ list is available at ftp://tamsun.tamu.edu/pub/comet.

Impact Questions and Answers

Impact Questions and Answers

Q3.1: What were some of the effects of the collisions?

Just before the the first comet fragment hit Jupiter, Zdenek Sekanina wrote that based on Hubble Space Telescope observations in early July 1994 the fragments had effective diameters generally between 1 and 2 kilometers: "Although the evidence points to an apparently continuing disintegration of the large fragments in numerous discrete events, objects a few km across still seem to have been present in early July, and the temporal variations in the effective diameters are likely to be primarily a rotational effect of strongly irregular shape." [58] Would some of the fragments remain intact and create large fireballs or would the comet nuclei shatter before they reached Jupiter? Perhaps both came true. Some fragments created large fireballs that rose above the limb of Jupiter and left giant dark marks on the planet, while other fragments seem to leave little trace of their impact.

Fragment A struck Jupiter with its kinetic energy equivalent to about 225,000 megatons of TNT creating plume which rose about 1000 km above the Jovian cloudtops. It was not long before the Hubble Space Telescope images of the fireball and impact site of fragment A were downloaded by thousand of observers. Many were surprised to see any effects from Earth. "We were thinking that we were going to have to go in with a microscope and you know stretch the image as hard as we could to pull out anything, but its just blasting away at us...unbelievable." − Hal Weaver

Fragment B was about the same brightness as fragment A in the pre−impact images but its impact left a small mark on Jupiter that was observed by only a few observatories. Then fragments C, D, and E left marks similar the impact of fragment A while the impact of F was difficult to detect. The real show−stopper was fragment G which struck Jupiter with an estimated energy equivalent to 6,000,000 megatons of TNT (about 600 times the estimated arsenal of the world). The fireball from fragment G rose about 3000 km above the Jovian cloudtops and was observed by many observatories (mostly in infrared). As it turned out, visible−light−radiating fireballs were seen with large telescopes and many observers reported seeing the dark impact scars with telescopes as small as 5 cm in diameter.

Observers have detected some of the collisions using radio telescopes [57] but it appears that the light emitted during the entry of the fragments into the Jovian atmosphere was not observed from the ground in reflection from Jupiter's moons as predicted. The Galileo spacecraft images of impact W have now been downloaded and do show a light flash that lasted a few seconds, but it was not particularly strong and would probably not have been detected in reflection from a moon by the available ground−based instruments [56].

Many of the later impacts hit near the sites of earlier ones and the resulting features soon became very complex. The development of the new features on Jupiter has since been followed by many observers. While the smaller features have almost disappeared the larger complexes are still visible even in small telescopes. Currently it appears that some of the dark impact sites are overlapping to form a partial band. No one really knows how long the features will continue to be visible, but perhaps this band will still be visible during the next observing season.

In summary, some of the fragments of comet Shoemaker−Levy 9 disappeared before they reached Jupiter (J, M and P1), some impacts were generally difficult to detect (B, F, N, P2, Q2, T, U, and V), some fragments created dark impact sites that measured about half of an Earth−diameter across (A, C, D, E, H, Q1, R, S, and W) and others created impact sites that were at least an Earth−diameter across (G, K, and L). Clearly not all of the fragments of comet Shoemaker−Levy 9 were the same. The size of fragment A is thought to have been about 1 km across and the diameter of fragment G is thought to have been about 3 km.

Q3.2: What causes the fireballs?

Most models have shown that the fireball is accelerated upward due to the atmospheric pressure gradient, not by buoyancy. In fact, the fireball is denser than the surrounding atmosphere, so its buoyancy is negative and it is pulled back down by gravity. When the comet deposited its energy in Jupiter's atmosphere, it created a zone of hot, high−pressure gas along its trajectory. This channel of pressurized gas exploded because it had to expand into its lower−pressure surroundings. However, it was more confined underneath and along the sides by the higher ambient pressure of Jupiter's atmosphere. The easiest direction for it to accelerate was upward, where it was unconfined. It was also directed along its axis, because it must expand further in that direction before its pressure can drop. The result was that the hot vaporized cometary and atmospheric material was shot upward as if from a cannon. As it rose, the driving pressure dropped and it went into a ballistic trajectory (but because it was a gas it was also expanding and cooling). It went into free fall, and like a fly ball it reached a maximum height and arched back down. Because of this behavior, we call it a "ballistic fireball".

Q3.3: How does this differ from other phenomena called "fireballs"?

There are two other related phenomena that go by the same name. When the word "fireball" is used, it should be obvious from the context which is being described:

Meteor fireball : a brilliant meteor that may trail bright sparks. This phenomenon is associated with the meteor, or entry phase of a bolide.

Nuclear fireball : a nuclear fireball is dominated by interior radiative transport at temperatures of tens of millions of degrees. It normally rises bouyantly, like an air bubble in water, and leads to the familiar mushroom cloud. In some high atmospheric tests, fireballs with diameters greater than the atmospheric scale height were generated. These fireballs rose ballistically in a manner very similar to the SL9 impact fireballs.

Q3.4: What is the difference between a "fireball" and a "plume"?

There was some discussion among the modelers as to the most appropriate term. Now that these are observational, rather than just theoretical phenomena, it is more important to have concise definitions. Eventually everyone will converge on the same terms by consensus and common usage. In mean time, we recommend the following:

Fireball : The bubble of hot gasses consisting of a mixture of Jovian atmosphere and cometary material that is shot upward by the impact. In the first moments after impact it is very hot, incandescent, and radiating in the visible and near infrared (note that the term "fire" implies heat but not combustion).

Plume : The debris bubble after it has expanded and cooled adiabatically.

Obviously there is not a clear distinction between the two.

Q3.5: Why was there a gap between the apparent limb of Jupiter and the plumes or fireballs in the Hubble images?

It is important to distinguish between the limb of Jupiter and the terminator (or sunrise line) which was several degrees closer from our perspective. In fact, the Hubble images show the luminescent fireball above the dark limb of Jupiter only 1–2 minutes after the fragment G impact. The apparent gap in this image is between the limb and the terminator. A few minutes later, the fireball has risen high enough to be in sunlight.

There is also a gap due to the shadow of Jupiter on the plume. The debris cloud that makes up the plume has risen into sunlight as we predicted in our "Watching for Fireballs" paper (EOS, July 5). The earth, Jupiter and the Sun were not in a straight line at the time of impact, so the plume had to rise hundreds of kilometers higher than the limb to reach sunlight.

Q3.6: How deep did the fragments penetrate into Jupiter's atmosphere?

That is currently one of the more controversial issues. We have not seen enough data yet to come to any firm conclusions, but we believe that the lack of spectral signatures for water is not sufficient evidence to conclude that the penetration was shallower than expected. David Crawford's simulations have indicated that, contrary to what many scientists have been saying, deep penetrations do not necessarily bring up a lot of deep material into the plume where it can be seen.

Q3.7: What is the dark material at the impact sites?

The dark semicircles south of the impact points are probably an ejecta blanket composed of fine material condensed from the plume. This material is either from the comet itself or from Jupiter and is suspended in the upper atmosphere. Some scientist refer to it as soot. In the infrared they look bright because of reflected sunlight and in the visible spectral region they are generally darker than the Jovian clouds.

The composition of the plumes was investigated by spectroscopy in many different wavelengths. No new molecules have been found but it is expected that further analysis will eventually make it possible to document chemical processes that took place. The following elements and molecules have been seen in the spectra: Li, Na, Mg, Mn, Fe, Si and S; NH3, CO, H2O, HCN; H2S, CS, CS2, S2; CH4, C2H2, C2H6, and possible others [56].

Q3.8: How can the structure of the impact sites be explained?

One of the most well know images is the HST image of the G impact site just after its appearance on the limb of Jupiter. There are a few features that stand out on this image:

- a dark thin ring,
- a dark streak inside this ring,
- a broad horseshoe−shaped feature to the south,
- and a small black spot toward the following limb.

The small black spot is actually the impact site of fragment D that stuck Jupiter the day before fragment G hit. The thin ring is possibly a shock wave in the atmosphere moving outward from where the fragment exploded below the cloudtops. At the time the image was taken the ring measured about one half of an Earth−diameter. Andy Ingersoll says that the thin black ring was moving subsonically at 500 m/s. The dark streak inside this ring is probably the path of the fragment with the entry point being on the south end. Note that the streak ends near the center of the thin ring. The broad horseshoe−shaped feature appears to represent the resettling debris from the fireball. In some wavelengths the bands of Jupiter can be seen through this broad feature. When compared to impact simulations, this pattern fits quite well with a 45 degree angle of entry.

Q3.9: What were the impact times and locations?

Here is a summary of the SL9 impact and brightness times as reported on the

International Astronomical Union Circulars cited (IAU#). The IAU circular number cited should be referenced for complete description of brightness measurements and the wavelength observed. Not every observed report of specific impact is listed. If anyone has a more complete list, please send email to astro@tamu.edu.

OBSERVED SL9 IMPACT TIMES

FRAG	IMPACT DAY / UTC	PEAK	FADED	OBSERVED BY	IAU#
A	JUL16.844 / 2015	2018	----	Hubble Telescope	6023-24
	JUL16.845 / 2017		2043	Calar Alto Obs./Spain	6023
B	JUL17.122 / 0256		0313	KECK Obs./Mauna Kea	6024
C	JUL17.304 / 0718		0739	NASA/IR Telescope	6024
	JUL17.303 / 0716	0721	+1 hr	Okayama Obs./Japan	6024
D	JUL17.496 / 1154	faded in seconds		CASPIR/Austr.	6025
E	JUL17.637 / 1517		1523	Calar Alto Obs./Spain	6025
F	JUL18.060 / 0126	20min.		ESO/Chile	6026
G	JUL18.315 / 0734	**0738*	0810	SPIREX/South Pole	6026
H	JUL18.813 / 1931	+10 min		Calar Alto Obs.	6027
	JUL18.814 / 1932			Galileo Spacecraft	6031
	JUL18.815 / 1934	1945		ESO/Chile	6027
K	JUL19.434 / 1025	short flash		Okayama Obs./Japan	6028
L	JUL19.926 / 2213	2218		Calar Alto Obs./Spain	6029
	JUL19.933 / 2224	2226		Rio de Janero Obs.	6029
	JUL19.929 / 2218			Galileo Spacecraft	6031
#M	JUL20.259 / 0613	0711		Mexican Natl. Obs.	6030
	JUL20.256 / 0609			KECK Obs./Mauna Kea	6030
N	JUL20.441 / 1036	1037		IRIS	6030
	JUL20.441 / 1036	faint flash 1038		CASPIR/Austr.	6030
P	--- No impact observed ---				6031
Q2	JUL20.822 / 1944	faint flash only		Pic du Midi Obs.	6032
Q1	JUL20.842 / 2012	2020 2nd flash		Pic du Midi Obs.	6032
	JUL20.848 / 2021			La Palma/Nordic Team	6031
R	JUL21.237 / 0541	**0543*	0609	CASPIR/Austr.	6032
	JUL21.233 / 0536	0546	0612	Palomar Obs.	6032
S	JUL21.640 / 1522	1529	1537	South African Obs.	6033
	JUL21.645 / 1529		1533	Calar Alto Obs./Spain	6033
T	--- No impact observed ---				6034
U	--- No impact observed ---				6034
V	--- No impact observed ---				6034
W	JUL22.340 / 0810	**0812*		CASPIR/Austr.	6034
	JUL22.343 / 0812	0815		IRIS	6034

NOTES: IMPACT - Time of impact or 1st light detected
PEAK - Time of peak brightness or start of Peak (reports varied)
** - Time detector saturated
FADED - Start of fade or when = Jup. brightness (reports varied)
#M - Missing fragment "M" impact observed

POST–CRASH IMPACT TIMES AND IMPACT LOCATIONS
FOR FRAGMENTS OF COMET SHOEMAKER–LEVY 9

FRAGMENT NAME	DATE JULY'94	PREDICTED TIME (UT) HH:MM:SS	ACCEPTED IMPACT TIME & 1-sigma error	JOVICENTRIC LATITUDE (deg)	SYSTEM II LONGITUDE (deg)
A	16	20:00:40	20:11:00 (3 min)	−43	119
B	17	02:54:13	02:50:00 (6 min)	−43	0
C	17	07:02:14	07:12:00 (4 min)	−43	158
D	17	11:47:00	11:54:00 (3 min)	−43	329
E	17	15:05:31	15:11:00 (3 min)	−43	86
F	18	00:29:21	00:33:00 (5 min)	−43	68
G	18	07:28:32	07:32:00 (2 min)	−43	318
H	18	19:25:53	19:31:59 (1 min)	−43	33
J	19	02:40	Missing since 12/93		
K	19	10:18:32	10:21:00 (4 min)	−43	209
L	19	22:08:53	22:16:48 (1 min)	−43	281
M	20	05:45	Missing since 7/93		
N	20	10:20:02	10:31:00 (4 min)	−44	6
P2	20	15:16:20	15:23:00 (7 min)	−44	184
P1	20	16:30	Missing since 3/94		
Q2	20	19:47:11	19:44:00 (6 min)	−44	338
Q1	20	20:04:09	20:12:00 (4 min)	−44	355
R	21	05:28:50	05:33:00 (3 min)	−44	334
S	21	15:12:49	15:15:00 (5 min)	−44	325
T	21	18:03:45	18:10:00 (7 min)	−44	75
U	21	21:48:30	21:55:00 (7 min)	−44	209
V	22	04:16:53	04:22:00 (5 min)	−44	84
W	22	07:59:45	08:05:30 (3 min)	−44	215

Notes : The impact times are from Don Yeomans and Paul Chodas. The impact time given is the time the impact would be seen at the Earth, if the limb of Jupiter were not in the way (i.e., the time listed is the time of impact plus the light travel time to the Earth). The impact latitudes are from pre–impact predictions and the system II impact longitudes were calculated using the accepted impact times. Approximate system III longitudes can be calculated by adding 67 degree to the system II longitudes. For information about how the accepted impact times were obtained see: http://newproducts.jpl.nasa.gov/sl9/impacts2.html

Q3.10: Where can I find more information and GIF images?

There is an article in the September 1994 issue of the ESO Messenger that is an excellent overview of the events [56]. The article is also available via the WWW at http://newproducts.jpl.nasa.gov/sl9/news35.html

There are over 700 images available involving comet Shoemaker–Levy 9. Here is a list of just a few images and animations that are available at seds.lpl.arizona.edu (128.196.64.66) and some info about how to get them if you only have mail access to files:

Comet Images : /pub/astro/SL9/images

- sl9−enh1.gif − March 28,1993 image of comet SL9 by Wieslaw Wisniewski
- sl9_930330.gif − March 30,1993 image of comet SL9 by Jim Scotti
- CometMay.gif − May 17,1994 image of comet SL9 by the Hubble Space Telescope

Impact Images : /pub/astro/SL9/images/recent/ALL

- CAO_A.gif − Impact A Fireball, Calar Alto Observatory
- HST_A.gif − Impact A Site, Hubble Space Telescope
- HST_Gplm.gif − Impact G Plume, Hubble Space Telescope
- HST_Gc.gif − Impact G and D Sites, Hubble Space Telescope
- LPM_FGH.gif − Impact F, G and H Sites, La Palma Swedish Solar Telescope
- PMO_L1.gif − Impact L Fireball, Pic du Midi Observatory
- GAL_W.gif − Impact W Fireball, Galileo Space Craft
- HST_R2.gif − Eight Impact Sites, Hubble Space Telescope

Impact Animations : /pub/astro/SL9/anim

- cao_a1.mpg − Impact A Fireball, Calar Alto Observatory
- keck−R.mpg − Impact R Fireball, Keck Telescope

Hartmut Frommert has compiled a list of GOPHER, FTP and WWW sites that contain images and information about the crash. His list (sl9−list.l*) is available at seds.lpl.arizona.edu in the /incoming directory. To receive his list by mail, send the following message (no subject) to ftpmail@seds.lpl.arizona.edu:

```
open
ascii
get /incoming/sl9-list.l10
quit
```

If you have only mail access to files then mail the following message (no subject) to bitftp@pucc.Princeton.edu or ftpmail@seds.lpl.arizona.edu:

```
HELP
```

MORE REFERENCES

48. Boslough, M.B., Crawford, D.A., Robinson, A.C., and Trucano, T.G. "Mass and penetration depth of Shoemaker−Levy 9 fragments from time− resolved photometry", Geophys. Res. Lett., Vol. 21, No. 14, pp. 1555− 1558, July 1, 1994.

49. Boslough, M.B., Crawford, D.A., Robinson, A.C., and Trucano, T.G. "Watching for fireballs on Jupiter", EOS−−Transactions of the American Geophysical Union, Vol. 75, No. 27, pages 305−310, July 5, 1994.

50. Crawford, D.A., Boslough, M.B., Trucano, T.G., and Robinson, A.C. "The impact of comet Shoemaker−Levy 9 on Jupiter", Shock Waves, in press.

51. Crawford, D.A., Boslough, M.B., Trucano, T.G., and Robinson, A.C. "The impact of periodic comet Shoemaker−Levy 9 on Jupiter", International Journal of Impact Engineering, accepted for publication.

52. Chapman, Clark R., "Dazzling demise of a comet", Nature 370, 245−246 July 28, 1994.

53. Glasstone, S. & Dolan, P.J. The Effects of Nuclear Weapons (U.S. Government Printing Office, 1977).

54. Beatty, J. Kelly and Goldman, Stuart J., "The Great Crash of 1994", Sky & Telescope, October 1994, pages 18−23.

55. MacRobert, Alan M. "Backyard Astronomy: Amateur Astronomy's Greatest Week", Sky & Telescope, October 1994, page 24−26.

56. West, R. M., "Comet Shoemaker−Levy 9 Collides with Jupiter: The continuation of a unique experience", ESO Messenger, September 1994.

57. O'Meara, Stephen James, "The Great Dark Spots of Jupiter", Sky & Telescope, November 1994, pages 30−35.

58. International Astronomical Union Circular No. 6020, July 15, 1994.

59. Eicher, David J., "Death of a Comet", Astronomy, October 1994, pages 40−45.

60. Burnham, Robert, "Jupiter's Smash Hit", Astronomy, November 1994, pages 34−39.

61. Eicher, David J., "Jupiter's Embattled Cloudtops", Astronomy, December 1994, pages 70−77.

Dan Bruton
astro@tamu.edu