THE HISTORY AND DYNAMICS OF COMET 9P/TEMPEL 1

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Abstract. Since its discovery in 1867, periodic comet 9P/Tempel 1 has been observed at 10 returns to perihelion, including all its returns since 1967. The observations for the seven apparitions beginning in 1967 have been fit with an orbit that includes only radial and transverse nongravitational accelerations that model the rocket-like thrusting introduced by the outgassing of the cometary nucleus. The successful nongravitational acceleration model did not assume any change in the comet's ability to outgas from one apparition to the next and the outgassing was assumed to reach a maximum at perihelion. The success of this model over the 1967–2003 interval suggests that the comet's spin axis is currently stable. Rough calculations suggest that the collision of the impactor released by the Deep Impact spacecraft will not provide a noticeable perturbation on the comet's orbit nor will any new vent that is opened as a result of the impact provide a noticeable change in the comet's nongravitational acceleration history. The observing geometries prior to, and during, the impact will allow extensive Earth based observations to complement the in situ observations from the impactor and flyby spacecraft.

Keywords: comets, deep impact, space missions, 9P/Tempel 1, cometary dynamics

1. Introduction: Orbital History of Comet 9P/Tempel 1

Comet 9P/Tempel 1 was discovered in the constellation of Libra on April 3, 1867 in Marseille, France by the itinerant German lithographer and part time astronomer, Ernst Wilhelm Leberecht Tempel (see Appendix 1). It was the first discovery of a periodic comet by Tempel and the ninth periodic comet to be recognized as such, as the designation "9P" indicates. Tempel described the comet as having a coma diameter of 4–5′ and before the comet's last observation by J. F. J. Schmidt at Athens on August 27, several observers commented upon the distinct or star-like nucleus (Kronk, 2003). On May 4 and again on May 8, 1867, William Huggins observed the comet with a spectroscope and noted that this comet, like comet 55P/Tempel-Tuttle that he had observed one year earlier on January 8, had a continuous spectrum. However for comet Tempel 1, Huggins only suspected the three spectral lines (i.e., C_2 Swan bands) that were observed with the brighter comet 55P/Tempel-Tuttle. Comet 9P/Tempel 1 was the third comet to be observed spectroscopically; the first was yet another Tempel discovery (1864 N1 Tempel), a non-periodic comet spectroscopically observed by G. B. Donati at Florence in August 1864 (Yeomans, 1991).

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The first elliptic orbit solution for comet 9P/Tempel 1 by K. C. Bruhns demonstrated that the comet was of short period (5.7 years) and a perturbed ephemeris by H. Seeliger allowed the comet to be recovered at Marseille by E. J. M. Stephan on April 4, 1873. It was followed by a number of astronomers to July 1. At its next apparition, Tempel, who was now observing from Arcetri, Italy, recovered the comet on April 25, 1879 (Kronk, 2003). A close Jupiter approach in 1881 (to within 0.56 AU) pushed the comet's perihelion passage distance out to 2.1 AU so that – despite attempts to recover the comet – it was not seen again for nearly a century (see Figure 1). Beginning with orbital elements derived from the nineteenth century observations, Marsden (1963) integrated the perturbed motion of the comet forward to 1972 and noted that due to Jupiter approaches in 1941 and 1953, the perihelion distance evolved back in toward the Earth's orbit with the perihelion distance being about 1.5 AU. Search ephemerides were issued and the comet was again observed during the favorable 1972 return to perihelion. As a result, a single image taken by Elizabeth Roemer on June 8, 1967 was also confirmed as comet Tempel 1. In addition to the nineteenth century returns to perihelion, the comet has been observed at its 1967, 1972, 1978, 1983, 1989, 1994, and 2000 returns.

Figures 1 and 2 show the time evolution of the comet's perihelion and aphelion distances along with the inclination changes with time. Dramatic orbital changes are due to Jupiter close approaches; Table I presents the planetary close approaches over the interval 1600–2400. Plots similar to those in Figures 1–2 were also presented in

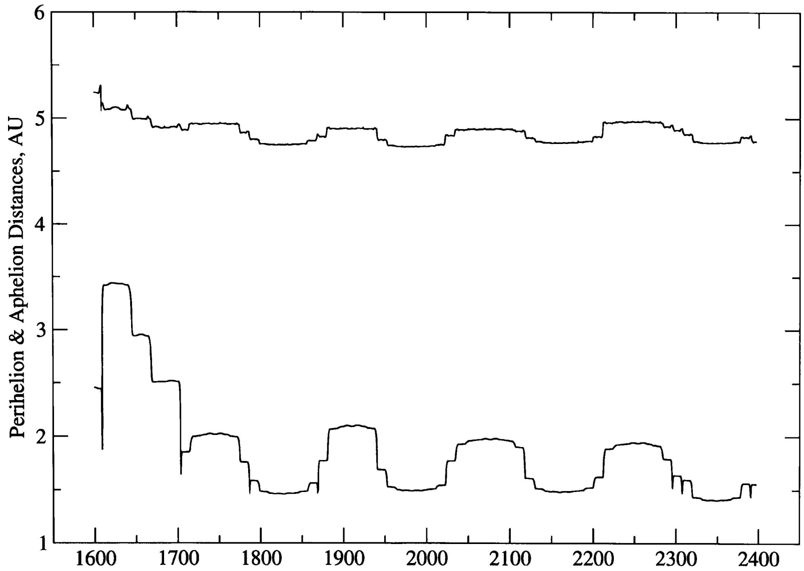

Figure 1. The evolution of the comet's perihelion and aphelion distances are presented over the 1600–2400 interval. The changes result primarily from the Jupiter close approaches noted in Table I. The changes in the perihelion and aphelion distances are due primarily to corresponding changes in the semi-major axis.

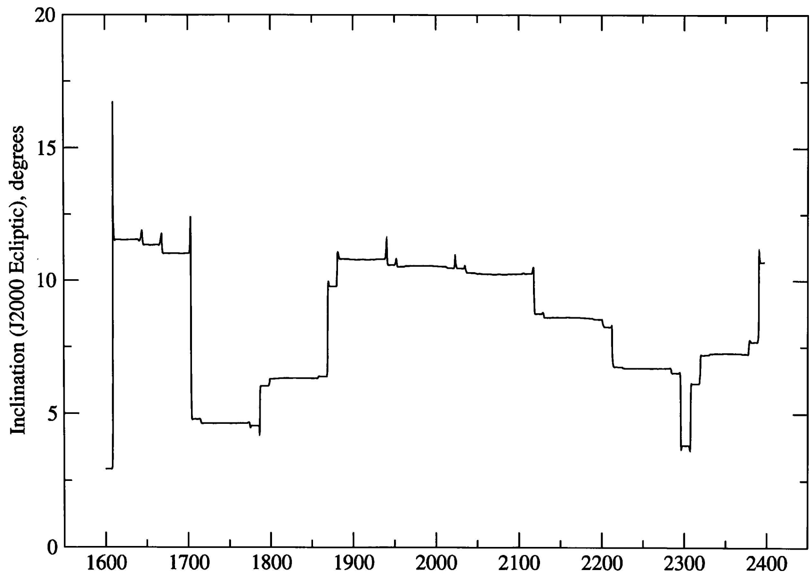

Figure 2. The evolution of the comet's orbital inclination over the 1600–2400 interval.

Carusi *et al.* (1985). It is clear that the evolution of the orbital comet is inextricably linked to its frequent approaches to Jupiter – approaches that move the perihelion distance into 1.5 AU and out to 2 AU with some regularity. Because the orbital period of comet 9P/Tempel 1 is nearly one half that of Jupiter, the comet's current orbital motion is close to a 2:1 resonance with Jupiter and hence its motion is rather stable, without dramatic variations in its orbital evolution. The uncertainties in the comet's nongravitational acceleration model, coupled with rather a close Jupiter approach in 1609, prevented a meaningful extrapolation of the comet's motion prior to the early seventeenth century.

2. Modeling the Nongravitational Acceleration of Comet 9P/Tempel 1

When modeling the motion of active comets, the rocket-like thrusting due to the sublimation of the ices must be taken into account and there have been many attempts to model these so-called nongravitational accelerations (Yeomans *et al.*, in press). The model that is most often employed is based upon the vaporization rate of water ice as a function of heliocentric distance whereby the outgassing is assumed to act symmetrically with respect to perihelion (Marsden *et al.*, 1973). In general, two nongravitational acceleration parameters are included in the orbital solution, where A1 is the acceleration acting in the radial (R), Sun-comet direction at 1 AU from the Sun and A2 is the corresponding transverse (T) acceleration acting in the comet's orbit plane, normal to the radial direction and positive in the

TABLE I

For the interval 1600–2400, planetary close approach distances (CA distance) in AU are noted, as are the corresponding relative velocities of the encounters in km/s.

Date (CT)	Body	CA distance	V_{rel}
1609 Feb. 20.8	Jupiter	0.106	5.029
1644 Nov. 25.7	Jupiter	0.732	4.906
1668 Jul. 23.8	Jupiter	0.662	4.810
1703 Nov. 02.5	Jupiter	0.199	4.583
1715 Apr. 03.6	Jupiter	0.987	6.679
1775 Jul. 04.4	Jupiter	0.651	5.475
1787 Mar. 10.2	Jupiter	0.348	4.535
1870 Feb. 01.9	Jupiter	0.359	4.471
1881 Oct. 19.8	Jupiter	0.553	4.780
1885 Apr. 23.9	Pallas	0.033	16.888
1941 Oct. 12.6	Jupiter	0.412	5.090
1953 Sep. 12.0	Jupiter	0.759	6.038
2011 Nov. 11.9	Ceres	0.041	10.103
2024 May 26.8	Jupiter	0.551	5.281
2036 Apr. 07.2	Jupiter	0.911	6.169
2119 Nov. 29.0	Jupiter	0.497	4.861
2183 Oct. 17.8	Mars	0.019	6.579
2214 May 10.1	Jupiter	0.469	5.054
2297 Dec. 21.2	Jupiter	0.380	4.262
2309 Dec. 19.0	Jupiter	0.395	4.469
2322 Jan. 08.0	Jupiter	0.880	6.551
2357 Jan. 03.2	Mars	0.034	7.593
2393 Jan. 05.5	Jupiter	0.390	4.490

direction of the comet's orbital motion. A third component (A3), acting normal to the comet's orbital plane such that $N = R \times T$, is occasionally necessary as well. A function, $g(r)$, expresses the water ice vaporization rate as a function of heliocentric distance (r) so that, for example, A1 $g(r)$ gives the radial outgassing acceleration acting upon the comet's nucleus at a particular heliocentric distance. In addition, due to seasonal outgassing effects, the outgassing need not reach a maximum at perihelion. Yeomans and Chodas (1989) introduced an asymmetric nongravitational acceleration model that allows the outgassing to reach a maximum a certain number of days (ΔT) before or after perihelion. In the current JPL small body orbit determination software, any combination of A1, A2, A3, and ΔT can be solved for in the orbital solutions.

For comet Tempel 1, there are astrometric observations at each of the seven modern returns to perihelion (1967–2000), and the observations from all of these apparitions can be successfully included into a single orbital solution using radial and transverse nongravitational accelerations that peak at perihelion. In addition to the nongravitational accelerations, the perturbative actions of the nine planets as well as Ceres, Pallas and Vesta were taken into account at each variable time step in the numerical integration. Successful orbital solutions over the 1967–2003 interval were obtained using $\Delta T = 0$ and constant values for A1 and A2. At first look, this suggests that the comet's ability to outgas is symmetric with respect to perihelion and the ability of the comet to outgas has not changed significantly during the previous seven apparitions. However, Lisse *et al.* (2005) notes that narrow band observations of OH in 1983 and 1994 imply either that the outgassing has a broad peak centered about 2 months prior to perihelion and dropping by a factor of three at perihelion, or the 1994 apparition was systematically a factor of two fainter than the 1983 apparition. In addition, the 1994 gas production rate at perihelion was down by a factor of 1.5–2 compared to the pre-perihelion peak. In light of these results, it seems clear that the nongravitational accelerations affecting the motion of comet 9P/Tempel 1, among the smallest for any active short periodic comet, do not allow meaningful constraints to be placed upon any secular changes in the comet's outgassing. Moreover, there is no appreciable signal in the astrometric data for an out-of-plane (A3) nongravitational acceleration or an asymmetric outgassing with respect to perihelion (ΔT). However, it seems unlikely that the rotation pole has significantly altered its position in space over the 1967–2003 interval since this should have introduced detectable changes in the values of A1 and A2.

Some 706 observations were fit over the interval June 8, 1967 through Dec. 26, 2003 with a resultant weighted RMS residual of $0.85''$. Planetary ephemeris DE405, from JPL, was utilized for the planetary coordinates and masses at each time step (Standish, 1998) (Table II).

TABLE II

The osculating orbital elements for comet 9P/Tempel 1 are presented along with the formal 1-sigma uncertainties in parentheses. JPL orbital solution K058/3 was employed.

EPOCH	2005 July 9.0 E.T.
Eccentricity, e	0.5174906 (0.0000001)
Perihelion distance, q (AU)	1.5061670 (0.0000003) AU
Perihelion passage time, T	2453556.81530 (0.00014) = 2005 July 5.31530 E.T.
Argument of perihelion, ω (°)	178.83893 (0.00007)
Longitude of the ascending node, Ω (°)	68.93732 (0.00006)
Inclination, I (°)	10.53009 (0.00001)
A1 (AU/day^2)	0.0091 (0.0029) $\times 10^{-8}$
A2 (AU/day^2)	0.00176 (0.00002) $\times 10^{-8}$
Semi-major axis (AU)	3.1215
Orbital period (years)	5.515

3. Orbital Perturbations as a Result of Deep Impact Itself

The Deep Impact collision with comet 9P/Tempel 1 takes place near the comet's perihelion point and at a relative velocity of 10.2 km/s. Using the formulation outlined by Ahrens and Harris (1994), we can estimate the recoil velocity resulting from an impacting body. We assume the comet's weak structure is in a gravity regime and the collision is partially elastic in the sense that the ejecta causes a momentum transfer above that of an inelastic collision. With a relative velocity of 10.2 km/s and impactor and cometary masses of 360 and 9×10^{13} kg respectively, the impactor will impart a very modest 0.00005 mm/s velocity change in the comet's orbital motion. The comet is traveling at a greater velocity than the impactor, so it will overtake and collide with it. Since the incoming impact direction is 15.2° Sunward from the comet's velocity vector and just 1 day prior to perihelion, the impact will introduce a perturbative impulse nearly opposite to the comet's orbital motion. This impulse direction and time is nearly optimal for secularly decreasing the comet's semi-major axis and hence decreasing its orbital energy and period. Figure 3 plots, as a function of time, the position differences between a comet that is perturbed and one that is unperturbed by the impact. By the time of the perihelion passage in 2022, these differences do not even reach 250 m. If the comet were in a strength regime, the resulting differences would be still less. Because the comet is so much larger and more massive than the impactor, the changes imparted in the motion of comet Tempel 1 by Deep Impact are completely negligible, especially

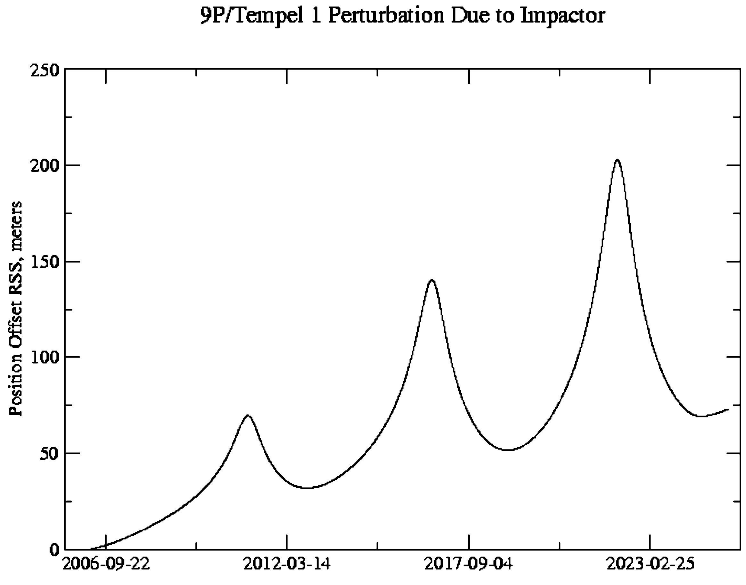

Figure 3. Position differences between a comet perturbed and unperturbed by the spacecraft impact, plotted as a function of time.

when compared to the orbital changes on the comet due to periodic passages near the giant planet Jupiter (e.g., 34 billion meter change due to the passage by Jupiter in 2024).

It has been suggested that one effective technique for deflecting a small comet or asteroid that is on an Earth threatening trajectory would be to run into it with a massive spacecraft at high velocity several years prior to its predicted Earth encounter. The optimal technique for this type of kinetic energy impact would involve a head on crash of a massive spacecraft with the comet near perihelion causing it to lose a bit of its orbital energy and hence change its orbital velocity by a few millimeters per second. Over a period of 10 years' time, a 4 mm/s change in the comet's velocity would modify its orbital position by one Earth radius thus allowing the comet to miss the Earth entirely. Although, the impulse given to the 6 km sized comet 9P/Tempel 1 in 2005 will not materially affect its orbit, this same impact magnitude could substantially affect the trajectory of a much smaller comet. For example, the impulse delivered to comet Tempel 1 in 2005 would be sufficient to move, in 10 years time, a comet of diameter 150 meters by one Earth radius.

4. Possible Orbital Perturbations by a New Vent Being Opened by Deep Impact

While any cometary orbital change due to the impactor's impulse will go unnoticed, the question remains as to whether or not the opening of an active vent on the comet's surface might introduce an observable change in its nongravitational acceleration. The following rough computation suggests that this will be a difficult effect to observe with confidence. For the isotropic outflow of cometary gases at a terminal velocity (V) on the surface of the nucleus with radius R, the gas pressure (P_g) is

$$P_g = \frac{NV}{4\pi R^2}$$

where N is the gas production rate in kg/s. At a heliocentric distance of 1.5 AU, the gas production rate is about 1.5×10^{28} molecules/second (Belton *et al.*, 2005). Assuming a mean atomic weight of 20.4 for the (mostly water) gas, a gas terminal velocity of 800 m/s and a nucleus radius of 3.0 km, the gas pressure would then be 3.6×10^{-3} N/m^2. For an impactor crater radius of 50 meters, the crater surface area would be about 7.9×10^3 m^2 with the nongravitational force acting upon the nucleus being 28 N. Dividing this force by the comet's assumed mass then gives the total acceleration acting upon the comet's nucleus as 3.1×10^{-13} m/s^2. This acceleration can then be compared to the computed nongravitational acceleration. This latter acceleration, in the radial direction, is just the value for A1 scaled from 1 to 1.5 AU using the $g(r)$ expression given by Marsden *et al.* (1973). With $g(r) = 0.36$

for $r = 1.5$ AU, the radial nongravitational acceleration computed from the orbit determination process is A1 $g(r) = 6.6 \times 10^{-10}$ m/s^2. Hence, a new active vent opened as a result of the impactor would only contribute about 1/2000 the value of the pre-existing radial nongravitational acceleration. Even if the computed gas pressure value were a factor of 10 higher because the nucleus had only a 10% active area, the new nongravitational acceleration (due to the impactor) would still be only 1/200 times the value of the pre-existing nongravitational acceleration. Although the pre- and post-encounter solutions for the nongravitational parameters (A1 and A2) will be carefully monitored, a first rough estimate of the likely effects do not suggest that any changes will be noticeable in the orbit determination solutions.

5. Ground Based Observational Circumstances for the Deep Impact Collision

Figure 4 displays the comet Tempel 1 observing conditions for the returns to perihelion in 1983, 1989, 1994, 2000, 2005, and 2011 presented in a rotating coordinate system so that for any particular return to perihelion, the positions of the Earth and Sun are fixed. The comet's positions with respect to the Earth and Sun are plotted as open circles at 30-day intervals before and after the perihelion point, which is denoted as a filled in circle. The 3 o'clock position (vernal equinox) represents the Earth's fixed location for a perihelion passage time of September 21, while the 12, 9 and 6 o'clock positions represents the Earth's locations for comet perihelion passages on December 21, March 21 and June 21 respectively. Using this plot, one

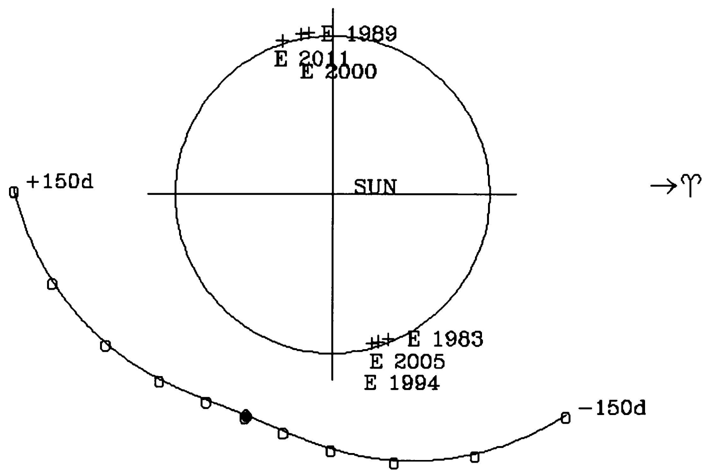

Figure 4. For perihelion passages in 1983, 1989, 1994, 2000, 2005, and 2011, the motion of comet Tempel 1 relative to a fixed Earth is shown in a rotating reference system. The positions of the comet are shown at 30-day intervals from 150 days before perihelion (−150 d) to 150 days after perihelion (+150 d).

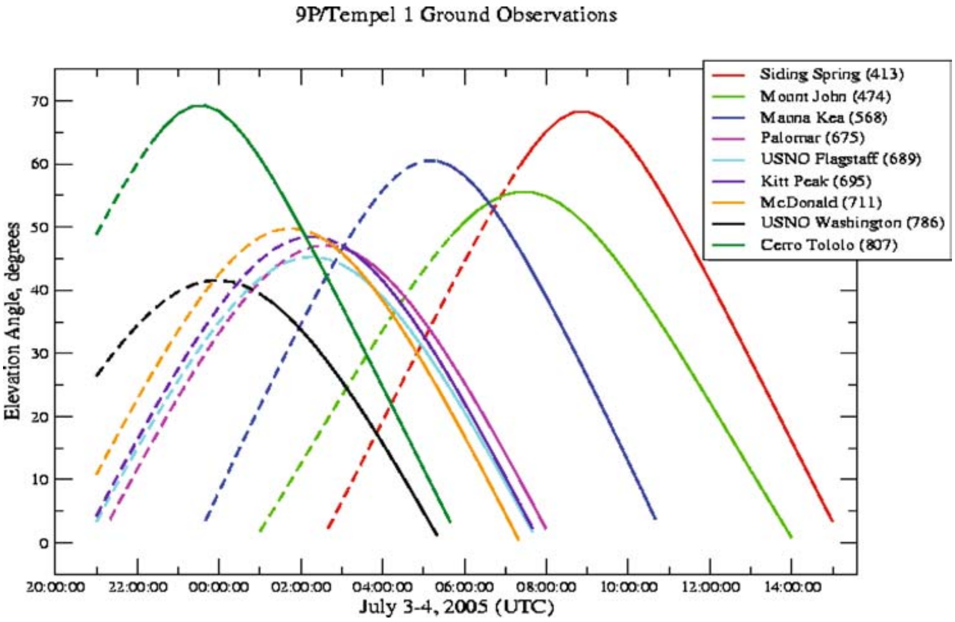

Figure 5. For various observatories, elevation angles for comet Tempel 1 are presented for several hours on either side of the cometary collision, which is scheduled for an Earth receive time of 6:00 UT on July 4, 2005. The actual impact time is 7 min and 26 s earlier. In each case, the dashed curve becomes solid at the end of nautical twilight.

can easily note that while the perihelion passages in 1989, 2000, and 2011 are extremely unfavorable since the comet reaches perihelion near solar conjunction, the 1983, 1994 and 2005 returns to perihelion have nearly identical, and very favorable, viewing conditions since the comet returns to perihelion near opposition. Due to the comet's 5.5-year orbital period, alternate returns to perihelion are favorable for ground-based viewing.

For the interval of time surrounding the impact itself, Figure 5 plots the elevation angle of the comet above the local horizon for nine observatories. In each case, the broken line becomes solid when nautical twilight ends (i.e., the Sun's zenith distance reaches 102°). For ground-based observations of the impact itself, and immediately thereafter, observatories in Hawaii and New Zealand are favored although observatories in the southwestern United States will have low-altitude viewing as well.

Figure 6 shows a sky plot of the comet from early December through the end of July 2005. Both the comet, and nearby Jupiter, will be in retrograde loops during the months of February, March, and April 2005. The comet's pre-impact apparent magnitude will be about 10 with a short tail pointing away from the bright star Spica (0.9 magnitude) less than 4° away in the constellation of Virgo. Depending upon how much dust is ejected as a result of the impactor on July 4, 2005 the comet's

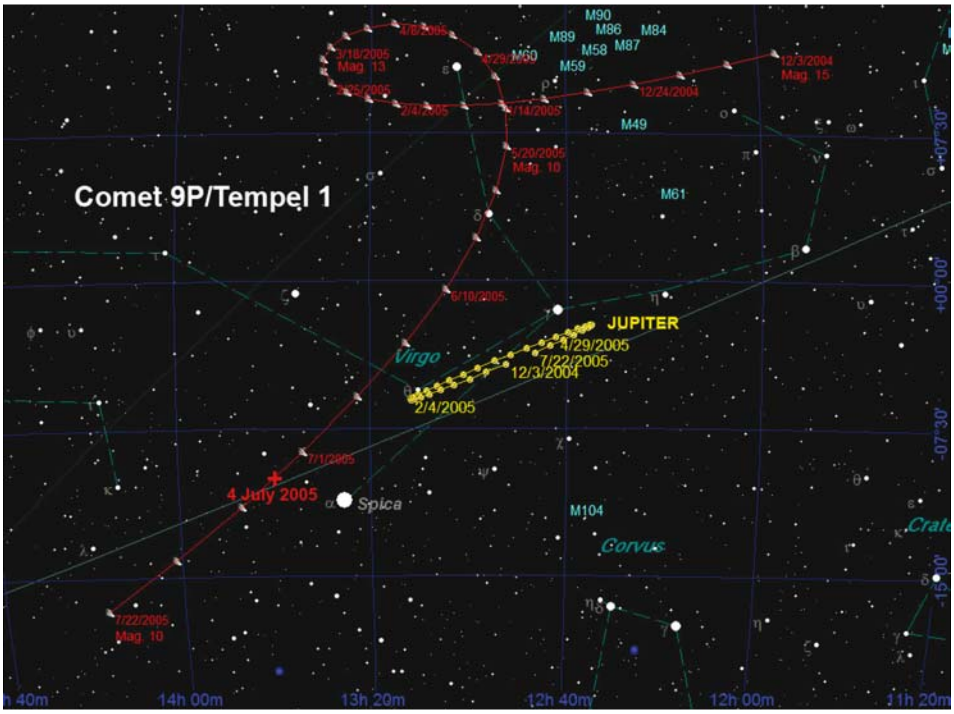

Figure 6. The apparent motion of comet Tempel 1 on the celestial sphere is illustrated from early December 2004 through late July 2005. Both the comet and nearby Jupiter undergo retrograde loops during this interval. Illustration provided by Dale Ireland.

apparent magnitude could increase by a few magnitudes but whether or not the brightening will be sufficient to render the comet a naked eye object remains to be seen.

6. Summary

The orbital period of comet 9P/Tempel 1 is about half that of Jupiter and, as a result, the comet's recent orbital evolution is controlled by its frequent close approaches to that planet; the comet's perihelion distance is periodically lowered to about 1.5 AU, raised to just over 2 AU, and then back again.

The comet was discovered in 1867, observed for two subsequent returns to perihelion in 1873 and 1879 and then, as a result of Jupiter close approaches, the perihelion distance was raised and the comet was not seen again until 1967, a century after its discovery.

As is the case for almost all active periodic comets, a successful orbital solution for comet Tempel 2 required the use of a nongravitational acceleration model to represent the rocket-like thrusting of the cometary outgassing as a function of heliocentric distance. More than 700 astrometric observations over the comet's seven modern apparitions (1967–2003) have been successfully represented with a single orbital solution that included constant values for the nongravitational parameters A1 and A2, where A1 and A2 are the radial and transverse nongravitational accelerations acting upon the comet at 1 AU from the Sun.

The constancy of A1 and A2 over the 1967–2003 interval suggests, but does not prove, that the comet's rotation axis has remained relatively fixed in inertial space. Was this not the case, one would expect the parameters A1 and A2 to have changed their values with time.

Despite the planned collision of the Deep Impact spacecraft with the comet's nucleus on July 4, 2005, there will only be a negligible 200 m, or less, modification to the comet's orbital position after 20 years.

While the spacecraft impact may open up a new active area on the surface of the nucleus, it seems unlikely that this additional activity will be sufficient to cause a measurable effect in the comet's subsequent orbital behavior.

At the time of the impact, and shortly thereafter, the comet will be observable in a dark sky from a number of different locations (e.g., southwestern United States, Hawaii, New Zealand). At the time of the impact, the comet will be 0.89 AU from the Earth with a predicted pre-impact apparent magnitude of about 10. It will be located in the constellation Virgo, $<4^\circ$ from the first magnitude star, Spica.

Subsequent to the impact, and depending upon the amount of dust excavated and thrown into the comet's atmosphere, the comet's apparent magnitude could brighten by several magnitudes.

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Appendix. The Discoverer of Comet Tempel 1: Ernst Wilhelm Leberecht Tempel (1821–1889)

An artistic free spirit, Ernst Tempel was born on December 4, 1821 in Saxony, one of 12 children. Of poor circumstances, Tempel received only a modest education and became largely self-educated. Upon reaching his twentieth year, Tempel began employment in Copenhagen as a lithographer. After 3 years, he continued his artistic talents in Venice Italy. Having acquired a keen interest in astronomy, Tempel purchased a 4-inch refracting telescope from the Bavarian K.A. von Steinheil and began systematic searches of the heavens from the balcony of a Venetian palace. His first discovery was on April 2, 1859 when he discovered the comet 1859 G1.

In March 1860, Tempel moved to Marseilles, France and remained attached to the Observatory there until the end of 1861 when he resumed work as a lithographer in Marseilles. In January 1871, the German Tempel was expelled from France by the Provisional Government. He traveled to Milan, Italy, where he became an assistant to Giovanni Schiaparelli at the Brera Observatory. Toward the end of 1874, Tempel became the assistant in charge of the Arcetri Observatory in Italy. This observatory had been erected in the years 1869–1872 from the designs of Giovanni Donati. However, after Donati's death in 1873, support for the Observatory declined and Tempel was forced to subsist on a meager salary with no funds to complete or maintain the observatory's two refracting telescopes. These instruments had apertures of 9.4 and 11 in.. Despite his difficulties, Tempel observed and recorded a considerable number of nebulae, often using his artistic skills to produce detailed drawings.

Along with the American Horace Tuttle, Tempel discovered the parent comet of the November Leonid meteors in 1866 (periodic comet 55P/Tempel-Tuttle). Among his cometary discoveries were three more periodic comets, 11P/Tempel-Swift-LINEAR in 1869 and comets 9P/Tempel 1 and 10P/Tempel 2 in 1867 and 1873. Along wyth the discovery of a total of 13 comets, Tempel also discovered five minor planets. For his first two discoveries in March 1861, the names Angelina and Maximiliana were proposed. Angelina was named in remembrance of the astronomical station of Baron F.X. von Zach near Marseilles while Maximiliana was named for Maximilian II, the king of Bavaria. The English astronomers John Herschel and George Airy along with some prominent German astronomers criticized both names because they broke with the tradition of using mythological figures as minor planet names. As a result, the name Maximiliana was changed to Cybele, a nature goddess of the ancient peoples of Asia Minor.

Born 2 years after the death of Tempel, the German surrealist painter, Max Ernst (1891–1976), saw a kindred spirit in Tempel's lust for adventure and the imperturbable joy he took in discovery. Ernst identified with Tempel's difficult life and sympathized with the troubles he encountered in finding suitable work in Germany because he lacked a formal education. One of Max Ernst's last artistic efforts was a collection of 39 lithographs that was dedicated to Tempel and appropriately named "Maximiliana."

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