1982JBAA...92..209B

Halley's Comet: AD 1986 to 2647 BC

JOSEPH L. BRADY

Lawrence Livermore National Laboratory, University of California, Livermore, California 94550, USA

In earlier predictions of the apparitions of Halley's Comet, a three- or four-day error, always with the same sign, has appeared consistently. By adding a secular term to the Newtonian equations of motion it has been possible to link the apparitions of 1910, 1835, 1759 and 1682 with a continuous numerical integration. This backward integration not only represents the last four apparitions but also remains remarkably close to the observed times of perihelion passage for more than 2000 years. The times of perihelion passage are compared to observed or derived dates back to 87 BC, and apparitions prior to 87 BC are compared with historical references whenever they could be found. The starting values of this long integration have been used to make a forward integration and to predict the 1986 return.

INTRODUCTION

Edmond Halley, in one of the first applications of Newton's law of gravity, computed the orbits of 24 comets[1]. He noticed that the comets of 1682, 1607 and 1531 had similar orbits and, with incredible insight, reasoned that the small differences in their periods could be due to the effect of Jupiter. With this evidence, Halley predicted that the comet of 1682 would return again in 1758. His detractors claimed that he purposely put the date beyond his possible lifetime so that he would not have to face the failure of his arrogant prediction. Of course the comet did return, being sighted on 1758 December 25. The periodicity of comets had been established. This comet, now known as Halley's Comet, has returned twice (1835 and 1910) since Halley's prediction. Historical research has identified Halley's Comet with other earlier comet appearances.

Before the comet returned in 1758, its orbit was computed more accurately by Clairaut[2], who took into account the effect of both Jupiter and Saturn. Uranus, Neptune and Pluto had not yet been discovered. Clairaut predicted 1759 April 13, but the comet came to perihelion March 12, one month earlier than expected. Of the several predictions for 1835, probably the best and certainly the most extensive was Rosenberger's[3], which missed the time of perihelion by four days. Neptune and Pluto had still not been discovered. The 1910 return was predicted by Cowell and Crommelin[4], who missed the perihelion passage by three days. They had neglected only Pluto which had not yet been discovered. In earlier papers by Brady and Carpenter[5,6], details of the next apparition of Halley's Comet were discussed and a perihelion passage of 1986 February 9.39474 was predicted. Included was a search ephemeris beginning in 1982.

If a prediction is to inspire confidence, the equations of motion upon which it is based should be as consistent as possible with the laws of physics, and the integration of the equations should be able to recover the past appearances accurately. Heretofore, all efforts to link more than two apparitions using Newtonian equations have invariably failed. A three- or four-day error, always with the same sign, appears again and again in the orbit calculations for Halley's Comet. However, by adding a secular term to the equations of motion, four apparitions (those of 1910, 1835, 1759 and 1682) were linked by a continuous numerical integration, which represented the almost 5000 observations to the contemporary accuracy of each apparition.*

When this integration was continued backward in time, even earlier apparitions were recovered, in most cases with a numerical accuracy greater than can be found from an analysis of the ancient observational records. This backward integration produced a 4600-year record of Halley's Comet. The calculated elements for these apparitions back to 87 BC have been published in the IAU *Catalogue of Cometary Orbits*[7]. They are found in Table I, along with the elements of 34 earlier apparitions not included in the catalogue because identification with historical records is uncertain. These elements may be of interest to historians of science and astronomy if further translations uncover new comet observations or records.

INTEGRATION OF THE EQUATIONS OF MOTION

The integration of the equations of motion has been discussed in an earlier paper[5], but it will be helpful to summarize the important points here. The work was done on a CDC 7600 computer,† which has a 48-bit word. The direct integration of the co-ordinates was

---

*For a discussion of the contemporary accuracy of each apparition, see Table I of reference 5.

†Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the US Department of Energy to the exclusion of others that might be suitable.

Table I

Elements of Halley's Comet from the Numerical Integration

	Perihelion passage				Equinox of 1950.0								
	Calendar date (T)	Julian date^a (T)	Eccentricity (e)	Semi-major axis (a)	Argument of perihelion (ω)	Longitude of node (Ω)	Inclination (i)	Mean daily motion (n)	Perihelion distance in a.u. (q)	Anomalistic period^b (P)	Keplerian period (P)	Epoch of osculation^c	M'^{d}
Gregorian calendar	1986 Feb 9.39	2446470.89474	0.9672774	17.9434699	111.°85700	58.°15403	162.°23840	46.″680059	0.5872	75.^{y}81	76.^{y}01	2446471.5	0.99992847
	1910 Apr 19.68	2418781.67876	0.9672985	17.9566617	111.71858	57.84637	162.21597	46.630330	0.5872	74.42	76.09	2418781.5	1.00000144
	1835 Nov 15.94	2391598.93816	0.9674001	17.9915606	110.68584	56.80246	162.25585	46.496385	0.5865	76.68	76.31	2391598.5	1.00007306
	1759 Mar 12.55	2363592.54924	0.9676948	18.0894800	110.68902	56.52836	162.36962	46.121066	0.5844	76.49	76.94	2363592.5	1.00014686
	1682 Sep 14.79	2335655.79463	0.9679429	18.1702827	109.19834	54.84581	162.26229	45.815446	0.5825	74.89	77.45	2335655.5	1.00022047
Julian calendar	1607 Oct 26.80	2308303.79922	0.9675142	17.9601890	107.52400	53.04742	162.89833	46.623378	0.5835	76.14	76.11	2308303.5	1.00029255
	1531 Aug 25.59	2280492.58830	0.9677759	18.0297653	106.94638	52.33215	162.91047	46.355459	0.5810	75.21	76.56	2280492.5	1.00036583
	1456 Jun 8.97	2253021.96963	0.9680212	18.1200431	105.80590	51.14235	162.88278	46.011127	0.5795	77.58	77.13	2253021.5	1.00043821
	1378 Nov 10.87	2224686.87263	0.9684058	18.2287716	105.26395	50.29558	163.10540	45.601782	0.5759	77.04	77.83	2224687.5	1.00051287
	1301 Oct 26.40	2196547.39829	0.9689503	18.4345779	104.46655	49.42588	163.06804	44.841921	0.5724	79.08	79.15	2196547.5	1.00058702
	1222 Sep 29.12	2167665.11535	0.9688781	18.4382709	103.81209	48.57594	163.18447	44.830154	0.5738	77.45	79.17	2167665.5	1.00066313
	1145 Apr 17.86	2139376.86091	0.9688238	18.4234786	103.66686	48.32755	163.21648	44.885829	0.5744	79.08	79.08	2139376.5	1.00073767
	1066 Mar 19.52	2110492.51507	0.9689107	18.4635196	102.43058	46.89317	163.10436	44.741596	0.5740	76.54	79.34	2110492.5	1.00081378
	989 Sep 2.99	2082535.98946	0.9679350	18.1319149	101.43720	45.82729	163.39149	45.976265	0.5814	77.13	77.21	2082535.5	1.00088744
	912 Jul 16.59	2054363.59268	0.9681204	18.1809472	100.72639	44.90943	163.30302	45.792098	0.5796	75.38	77.52	2054363.5	1.00096168
	837 Feb 27.88	2026830.88012	0.9678523	18.0956419	100.04899	44.19147	163.43994	46.117956	0.5817	76.77	76.98	2026830.5	1.00103423
	760 May 21.78	1998789.77841	0.9679045	18.1087908	99.94348	43.94779	163.43604	46.069435	0.5812	75.62	77.06	1998789.5	1.00110811
	684 Oct 6.73	1971168.73234	0.9682115	18.2112947	99.08927	43.05590	163.40978	45.682685	0.5789	77.56	77.72	1971168.5	1.00118090
	607 Mar 18.20	1942841.20053	0.9681073	18.1887506	98.73699	42.51456	163.46917	45.769349	0.5801	76.47	77.57	1942841.5	1.00125554
	530 Sep 26.89	1914909.88631	0.9687795	18.4107934	97.51886	41.22824	163.38697	44.945503	0.5748	79.26	79.00	1914909.5	1.00132914
	451 Jun 25.79	1885961.79103	0.9689866	18.4728969	96.96191	40.46294	163.47175	44.720745	0.5729	77.37	79.40	1885961.5	1.00140542
	374 Feb 12.56	1857704.55571	0.9686488	18.3835543	96.44210	39.82908	163.53502	45.048825	0.5763	78.81	78.82	1857704.5	1.00147987
	295 Apr 22.54	1828918.54056	0.9688230	18.4440749	95.18223	38.37198	163.36108	44.828976	0.5750	76.91	79.21	1828918.5	1.00155573
	218 May 27.56	1800829.56104	0.9680446	18.1662304	94.08893	37.17113	163.56607	45.863052	0.5805	77.13	77.43	1800829.5	1.00162974
	141 Apr 10.24	1772658.24221	0.9679289	18.1495084	93.68596	36.53716	163.43943	45.928152	0.5821	75.14	77.32	1772658.5	1.00170397
	66 Feb 19.97	1745214.97389	0.9676643	18.0568796	92.65988	35.46912	163.57113	46.283681	0.5839	76.37	76.73	1745214.5	1.00177629
	-11 Oct 8.64	1717321.63799	0.9674900	18.0234254	92.56278	35.24166	163.58337	46.414308	0.5859	75.25	76.52	1717320.5	1.00184979
	-86 Jul 10.40	1689837.39753	0.9678277	18.1528339	90.82474	33.40550	163.34836	45.920534	0.5840	77.05	77.34	1689837.5	1.00192220
	-163 Jun 22.38	1661695.37873	0.9678705	18.1347929	89.28534	31.57402	163.68488	45.990777	0.5827	76.56	77.23	1661695.5	1.00199636
	-240 Nov 30.64	1633732.63684	0.9681774	18.2565294	87.70882	29.79946	163.35018	45.533212	0.5810	76.13	78.01	1633732.5	1.00207004
	-316 Oct 15.78	1605927.78321	0.9676908	18.0686427	86.21681	28.17870	163.59208	46.246961	0.5838	76.49	76.80	1605927.5	1.00214331
	-392 Apr 22.19	1577992.18710	0.9675462	18.0490290	86.08381	27.85946	163.54785	46.324066	0.5858	74.77	76.68	1577991.5	1.00221692
	-467 Jul 16.05	1550683.04722	0.9675439	18.0614967	85.08223	26.82854	163.53143	46.277770	0.5862	76.27	76.76	1550683.5	1.00228887
	-543 Apr 10.57	1522827.56564	0.9672673	18.0005072	84.71771	26.30830	163.58208	46.514870	0.5892	75.52	76.37	1522827.5	1.00236227
	-619 Oct 5.17	1495246.16556	0.9669880	17.9302285	83.42638	24.75835	163.25669	46.790312	0.5919	73.93	75.92	1495245.5	1.00243495

Table I *(concluded)*

	Perihelion passage				Equinox of 1950.0								
	Calendar date (T)	Julian date[a] (T)	Eccentricity (e)	Semi-major axis (a)	Argument of perihelion (ω)	Longitude of node (Ω)	Inclination (i)	Mean daily motion (n)	Perihelion distance in a.u. (q)	Anomalistic period[b] (P)	Keplerian period (P)	Epoch of osculation[c]	M'[d]
Julian calendar	-693 Nov 1.66	1468244.65702	0.9669279	17.9087928	82°.05911	23°.35558	163°.36190	46″.876008	0.5923	$75^{\mathrm{y}}.47$	$75^{\mathrm{y}}.79$	1468244.5	1.00250610
	-768 May 13.79	1440679.79289	0.9670701	17.9371014	81.80241	22.93216	163.36115	46.766775	0.5907	75.37	75.97	1440679.5	1.00257873
	-844 Dec 29.45	1413150.45272	0.9667273	17.8408819	81.66838	22.58267	163.26419	47.147325	0.5936	73.16	75.36	1413150.5	1.00265127
	-917 Oct 31.78	1386427.77968	0.9668920	17.8995062	79.92924	20.87601	163.11184	46.917537	0.5926	75.63	75.73	1386427.5	1.00272169
	-992 Mar 15.39	1358804.39191	0.9671510	17.9641626	79.22748	19.94065	163.22387	46.666161	0.5901	75.67	76.14	1358804.5	1.00279448
	-1068 Jul 13.67	1331165.66659	0.9670353	17.9444281	79.02377	19.55616	163.16724	46.744862	0.5915	74.25	76.01	1331165.5	1.00286730
	-1142 Apr 15.50	1304047.50412	0.9671958	18.0193747	77.93666	18.46979	163.01429	46.455187	0.5911	76.15	76.49	1304047.5	1.00293876
	-1218 Feb 19.63	1276233.63136	0.9671247	18.0179703	77.37697	17.68090	163.10538	46.462315	0.5923	76.05	76.48	1276233.5	1.00301205
	-1294 Jan 31.98	1248455.98229	0.9667750	17.9398589	76.89378	16.92102	162.88438	46.767802	0.5961	73.86	75.99	1248455.5	1.00308525
	-1368 Mar 22.40	1221477.40115	0.9667221	17.9341501	75.38414	15.38839	162.88338	46.791793	0.5968	75.75	75.95	1221477.5	1.00315633
	-1444 Jun 21.56	1193809.56050	0.9669866	18.0006495	74.87227	14.68605	162.84504	46.534430	0.5943	75.86	76.37	1193809.5	1.00322924
	-1520 Aug 13.53	1166103.53444	0.9665998	17.8909480	74.71336	14.26641	162.71544	46.964796	0.5976	73.53	75.67	1166103.5	1.00330224
	-1593 Feb 2.27	1139247.26531	0.9667802	17.9539628	73.22770	12.80239	162.60303	46.719405	0.5964	75.93	76.07	1139247.5	1.00337301
	-1669 Feb 27.55	1111513.55407	0.9668650	17.9698793	72.95391	12.34081	162.64083	46.659046	0.5954	75.44	76.18	1111513.5	1.00344609
	-1745 Sep 19.62	1083958.62134	0.9665758	17.8963481	72.77907	11.95245	162.54360	46.948604	0.5982	73.81	75.71	1083958.5	1.00351869
	-1819 Nov 26.34	1056998.34086	0.9666875	17.9573684	71.72332	10.91927	162.40429	46.711159	0.5982	75.66	76.10	1056998.5	1.00358973
	-1894 Mar 29.42	1029362.41979	0.9666842	17.9705097	71.14720	10.12535	162.43743	46.661623	0.5987	75.80	76.18	1029362.5	1.00366256
	-1970 Jun 10.28	1001676.27516	0.9664427	17.9171631	71.16795	9.93255	162.36371	46.871877	0.6013	73.62	75.84	1001676.5	1.00373551
	-2044 Oct 25.64	974785.63621	0.9663588	17.9512005	69.75254	8.53663	162.16699	46.740279	0.6039	75.82	76.06	974785.5	1.00380637
	-2120 Dec 30.18	947092.18490	0.9664979	17.9971376	68.88589	7.39894	162.10957	46.563131	0.6029	75.94	76.35	947092.5	1.00387934
	-2195 Jan 22.39	919356.39348	0.9663083	17.9432843	68.60781	6.89758	162.08512	46.774616	0.6045	73.99	76.01	919356.5	1.00395242
	-2269 Jan 26.56	892331.55767	0.9666271	18.0528686	67.42317	5.72647	161.86083	46.351011	0.6025	76.52	76.70	892331.5	1.00402363
	-2346 Jul 21.33	864383.32685	0.9666740	18.0540638	67.06007	5.16574	161.90045	46.348108	0.6017	75.84	76.71	864383.5	1.00409727
	-2422 Sep 17.67	836682.66847	0.9660617	17.9035380	66.63830	4.42841	161.56924	46.935555	0.6076	73.88	75.75	836682.5	1.00417027
	-2496 Nov 1.17	809699.17446	0.9660654	17.9183495	65.48556	3.26510	161.51126	46.879031	0.6081	75.35	75.85	809699.5	1.00424137
	-2571 Jun 25.72	782176.72011	0.9659876	17.9074323	65.22509	2.82909	161.51321	46.923601	0.6091	75.19	75.78	782176.5	1.00431389
	-2646 Apr 18.29	754714.28940	0.9656677	17.8251489	65.30263	2.71081	161.45895	47.250587	0.6120	73.08	75.26	754714.5	1.00438625

[a] Prior to 1925 the decimal of the calendar day (whether using the Julian or Gregorian calendar) is in the older style Greenwich Mean Time which began at Greenwich noon. After 1925 the decimal is in Universal Time which begins at Greenwich midnight.

[b] $(T_i - T_{i-1})/365.2422$.

[c] The integration date from which the coordinates and velocity components were taken.

[d] $M' = M[1 - \epsilon\,(t - t_0)]$, where $\epsilon = 2.6350 \times 10^{-9}$ and $t_0 = 2419326.5$.

used with a constant time step of 1/2 day. Using Brouwer's expression[8] and a proportionality constant of 1/10, the buildup of round-off error after 200 years is 2×10^8. Thus, the calculation still provides seven good figures (better than modern observational accuracy). Even after 4000 years, the error is only 5×10^8, and six figures of accuracy remain. After 6000 years five good figures remain, and the time of perihelion passage can still be determined more accurately than ancient records require.

In attempting to link more than two apparitions, the classical Newtonian equations of motion were soon found to be inadequate, even with all of the nine known planets included. Because of this, an empirical secular term was added to the comet's equation of motion. With the addition of this term, the differential equation for the comet became

$$\frac{d^2x}{dt^2} + k^2M\left[1-\epsilon(t-t_0)\right]\frac{x}{r^3} = F_x ,$$

(and similarly for y and z), where k is the Gaussian constant, M is the combined mass of the Sun and comet, F_x is the perturbation due to the combined effects of all the planets, and $\epsilon(t-t_0)$ is the added secular term, with t_0 taken as the epoch of the starting values and ϵ determined from the observation residuals. These altered equations of motion were integrated by a modification of Cowell's method[9] with an n-body code[10]. The planetary starting values were those of Lieske[11], with the planetary masses modified according to Clemence[12].

With the addition of a free parameter such as ϵ, it should be possible to link three apparitions. However, this would not ensure the accuracy of the model any better than linking two apparitions without the parameter. Therefore, if we are to have confidence in the altered equation of motion as a predicting device, the comet's initial conditions and ϵ must be determined in such a way as to link at least four adjacent

Table II

Comparison of the Perihelion Dates as determined by Numerical Integration in the present work with those given by Kiang[17] and those given by Cowell and Crommelin[19]

Apparition	*Reference*	*Paraphrase of reference*
—316 Oct. 15.783 (317 BC)	20	Aristotle's pupil, Theophrastus, refers to comets seen between 330 and 290 BC.
—392 Apr. 22.187	21	In 394 BC, a comet was seen in Greece, followed by the great Corinthian War.
	20	Pliny refers to "beams", which appeared when the Spartans were defeated in the naval battle at Cnidus in 394 BC. This is thought to be a comet reference.
—467 July 16.047	22	According to Pliny and Damachus, about 465 BC an extraordinary object appeared in the sky for 75 days. Also Ma-Tuoan-Lin speaks of a comet in 466 BC which Pingré considered identical with the object visible in Europe in January.
	21	Lubienietzki mentions a comet seen over all of Greece for 75 nights in 466 BC. In the same year Sparta was nearly destroyed by an earthquake.
	23	During the tenth year of Tsin Tsao Kung (467 BC), a (hui) comet was seen.
	24	Obsequens, the 4th century Roman chronicler of strange and unusual events, tells of "burning skies". This is considered a comet metaphor.
	25	Anaxagoras is quoted as stating that for 75 days before the fall of the great meteorite of 467 BC, ". . . a body of extraordinary grandeur was seen".
—543 Apr. 10.566	26	Xenophon of Colophon observed a comet in the 540s.
—619 Oct. 5.166	27	Pingré believed that Jeremiah referred to this comet, and he cites the prophecy, "We shall see in the West a star such as is called a comet . . ," as an historical record of a comet seen in 618 or 619 BC.
—619 Oct. 5.166	28	In autumn, during the seventh month, in the 6th year of Chou Chhing-Wang (614 BC), a (hui) comet entered Pei-Tou (The Great Bear).
	26	About 626 BC, Jeremiah (1:2) saw a vision of a seething cauldron. This is thought to be a metaphoric description of a comet.
—693 Nov. 1.657		
—768 May 13.793		
—844 Dec. 29.453		
—917 Oct. 31.780		
—992 Mar. 15.392	29	Gunnar Norling considers the 'angel' seen at the site of King David's temple in Jerusalem as a bright comet. He adopts 989.8 BC as the foundation date of the temple. If the comet appeared in 993 BC, this would allow 3.2 years to build the temple, which is more reasonable than the 20 years needed to fit previous predictions.
—1068 July 13.667	30	A comet appeared at the time King Wu-Wang waged war against King Chou. The exact date is an open question, but dates from 1122 to 1030 have been suggested, with 1055 BC as the most probable.
—1142 Apr. 15.504	31	G. Smith, in his *History of Babylonia*, reports that at the time that Nebuchadnezzar invaded Elam, there appeared an enormous comet, the tail of which stretched like a great reptile from the north to the south of the heavens.
	32	A. H. Sayce, in his *Babylonian Inscriptions*, gives the following account of a comet seen during the campaign in Elam about 1140 BC: ". . . a star arose whose body was bright like the day, while from its luminous body a tail extended, like the tail of a scorpion".

apparitions. An iteration process, which slowly converged, was used to reduce the observation residuals to contemporary accuracy for the last four apparitions (1910, 1835, 1759 and 1682).* The starting values so determined and the plots of all the observations were shown in an earlier paper[5]. This orbit not only represents the last four apparitions but also remains remarkably close to the observed times of perihelion passage for more than two thousand years.

No matter how well the integration fits the past apparitions, it can be argued that whatever is causing the comet to deviate from Newtonian motion need not persist in the future (or at least need not persist in the manner implied by the added empirical term). However, the degree of confidence placed in the model should somehow be related to the length of time the model will fit the observed apparitions, and in this case, the length of time is more than two millennia.

The purpose of the secular term is to provide accurate predictions, both forward and backward in time, and this it appears to do. However, as used here, it has no reasonable gravitational interpretation and, therefore, must be labelled a non-gravitational force. It may then be directly related to F. L. Whipple's[13] icy-conglomerate model which, at present, is the most widely accepted way of accounting for the anomalous motion observed in many comets.

THE ELEMENTS OF HALLEY'S COMET: AD 1986 TO 2647 BC

From the numerical integration of the orbit, a set of co-ordinates and velocity components of the comet was selected at an epoch as close as possible to the time of each perihelion passage. These co-ordinates and velocity components were transformed into the angular elements shown in Table I. The data are completely consistent with a continuous integration using the following seven starting values:

Epoch of osculation = 2419326·5
$x_0 = -5{\cdot}75607\ 81727\ 009$
$y_0 = +2{\cdot}86170\ 47119\ 960$
$z_0 = -0{\cdot}88525\ 09134\ 848$
$\dot{x}_0 = -0{\cdot}00614\ 90168\ 10270\ 2$
$\dot{y}_0 = +0{\cdot}00606\ 94356\ 81837\ 6$
$\dot{z}_0 = -0{\cdot}00020\ 74564\ 47430\ 7$
$\epsilon = 2{\cdot}6350 \times 10^{-9}$

The accuracy of the data in Table I is such that an ephemeris can be constructed for any desired apparition to check historical records of ancient observations.

COMPARISON OF THE INTEGRATED TIMES OF PERIHELION PASSAGE WITH OBSERVATIONS

The first comprehensive compilations and translations of Chinese astronomical observations were done by Biot[14] and Williams[15]. Recently, Ho Peng Yoke[16] improved, corrected and extended these early catalogues. Kiang[17], using a combined computational and graphical method, derived the time of perihelion passage for apparitions back to 240 BC. Kiang's method is mainly a refinement of the method developed by Cowell and Crommelin[18] over half a century ago. At each apparition, Kiang made a correction of the perihelion time using the observational record. These perihelion times may be regarded as individual perturbed orbit calculations and are, in a sense, observational data. Undoubtedly some of these dates can still be improved, but on the whole the method is far more rigorous than that used by Cowell and Crommelin[18].

Table II shows a comparison of these two sets of perihelion dates with those obtained from the continuous numerical gravitational theory discussed herein. The column headed $\triangle T$ (Brady – Kiang) is the difference between the perihelion dates in Table I and those given by Kiang[17] in his Table V. The column headed $\triangle T$ (Brady – C. & C.) is the difference between the perihelion dates in Table I and those given in the BAA *Catalogue of Cometary Orbits 1960*[19], which, with a few exceptions, are the work of Cowell and Crommelin. Individual references for these dates may be found by consulting the BAA catalogue.

APPARITIONS PRIOR TO 241 BC

Table III lists the calculated dates of perihelion passage for apparitions prior to −240 (241 BC). Literary and historical references to comets seen at or near the computed time of the apparition are cited and paraphrased to add support to the predictions[20–32].

There are probably enough bright comets in any century to lend historical support to some other set of computed dates derived by a different method. Nevertheless, it is hard to imagine a comet as bright as Halley's going unnoticed. If the computed dates contained in Table III are close to reality, the phenomenon must have been observed at the calculated time. Of course, there is always the question of whether an apparition was recorded and whether the record has been found and translated. Even if the record is

---

*Only these four apparitions are telescopic. However, a few of the pre-telescopic observations are of relatively high accuracy, particularly the 1607 observations of Kepler (referred to by Bessel as little gold nuggets), the 1531 observations by Peter Apian, and the 1456 observations by Paolo Toscanelli.

Table III

Perihelion Passage Dates for Apparitions Prior to 241 BC

Year of apparition	ΔT *(Brady – Kiang)* days	ΔT *(Brady – C. & C.)* days	*Year of apparition*	ΔT *(Brady – Kiang)* days	ΔT *(Brady – C. & C.)* days
1910	0·00	0·00	760	−0·22	−20·22
1835	0·00	0·00	684	+8·73	−30·27
1759	0·00	0·00	607	+5·70	−1·80
1682	+0·02	0·00	530	+2·19	−49·11
1607	−0·26	+0·08	451	+1·79	−7·71
1531	+0·30	−0·20	374	−2·94	−0·44
1456	+0·37	+0·77	295	+2·54	+15·54
1378	+2·35	+2·10	218	+10·56	+51·56
1301	+3·52	+3·70	141	+21·74	+16·24
1222	−1·88	+19·12	66	+24·97	+24·97
1145	−3·64	−1·14	−11	+3·64	−0·66
1066	−3·78	−7·48	−86	−22·60	−35·60
989	−5·51	+0·49	−163	−104·62	−331·62
912	+7·59	−2·41	−240	−118·36	−165·36
837	+0·88	+2·88			

found, it is sometimes difficult to recognize the cometary metaphor.

Also, it should be remembered that most comet observations prior to 1835 were made from the northern hemisphere where an apparition can often be poor because of the geometry of the orbit. For example, after perihelion in 1835, when Halley's Comet had disappeared in Europe, Sir John Herschel saw it as a spectacular and bright object from the southern hemisphere[33].

It is customary to use the Julian calendar for dates before AD 1582, and this custom has been followed in Tables I and III. However, for remote dates, especially those mentioning seasonal events, it would seem better to use the Gregorian calendar, which would be in agreement with the Sun. According to Bickerman[34], even the Julian calendar is of little use prior to AD 8, because after Julius Caesar's death (44 BC), the pontifices erroneously inserted the intercalary day every three years instead of every four so that by 9 BC, Augustus had to omit the intercalation for 16 years to correct the error. This is only a small error with respect to the Sun, but in 46 BC the difference between the Roman calendar and the Sun was very large. For example, the solar eclipse of 190 BC March 14 was sighted in Rome on July 11, and the lunar eclipse of 168 BC June 21 was seen on September 4. To bring the months back to their right seasons, Julius Caesar abandoned the Roman calendar, inserted 90 days, and instituted his Julian calendar.

In general, few of the BC observation dates should be considered as anything but approximations. The conversion of dates in the many calendars of historical times to their exact equivalents in the Julian or Gregorian calendar is very difficult and often impossible. Bickerman[35] warns that when converting Greek or pre-Julian dates to the Julian calendar, the certainty is only to the approximate season. In converting Near Eastern dates, except for the Babylonian cyclical calendar or the Egyptian calendar, the error beyond 900 BC increases to 10 years or more in the 14th century BC, to 50 years in the 17th century BC, and to 100 years on earlier dates. Therefore, the observation of an 'extraordinary object' visible to Damachus and Pliny in January and February of about 465 BC[22] should not necessarily appear in contradiction with a comet of which Ma-tuoan-lin speaks, visible in 466 BC; and, indeed, Pingré considers the two to be identical.

ACKNOWLEDGEMENTS

This work was performed under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

REFERENCES

1 Halley, E., *Phil. Trans. R. Soc. Lond.*, **2971** (1705).
2 Plummer, H. C., *Nature*, **cl**, 251 (1942).
3 Rosenberger, O. A., *Astron. Nach.*, **xii** (276), 187 (1835).
4 Cowell, P. H., and Crommelin, A. C. D., *Greenwich Observations for the Year 1909* (appendix), Edinburgh, 1910.
5 Brady, J. L., and Carpenter, E., *Astron. J.*, **lxxvi**, 728 (1971).
6 Brady, J. L., and Carpenter, E., *Astron. J.*, **lxxii**, 365 (1967).
7 Marsden, B. G., *Catalogue of Cometary Orbits* (2nd ed.), Cambridge, Massachusetts, 1975.
8 Brouwer, D., *Astron. J.*, **xlvi**, 149 (1937).
9 Cowell, P. H., and Crommelin, A. C. D., *op. cit.* (ref. 4), 84.
10 McMahon, F. H., personal communication, Lawrence Livermore National Laboratory, Livermore, California (1970).
11 Lieske, J., *Newtonian Planetary Ephemerides 1800–2000, Technical Report 32-1206*, Jet Propulsion Laboratory, Pasadena, California, 1967.

12 Clemence, G., *Ann. Rev. Astron. Astrophys.*, **iii**, 101 (1965).
13 Whipple, F. L., *Astron. J.*, **cxi**, 375 (1950).
14 Biot, M. E., *Connaissance des temps*, 44, 60 and 69, Paris, 1846.
15 Williams, J., *Observations of Comets from BC 611 to AD 1640. Extracted from the Chinese Annals*, London, 1871.
16 Ho Peng Yoke, *Vistas in Astronomy*, **v**, 127, New York, 1962.
17 T. Kiang, *Mem. Br. astron. Assoc.*, **xxxix** (3), 27 (1961).
18 Cowell, P. H., and Crommelin, A. C. D., *Mon. Not. R. astron. Soc.*, **lxviii**, 111 (1907) and 173, 369, 510 and 665 (1908).
19 Porter, J. G., *Mem. Br. astron. Assoc.*, **xxxix** (3), 1 (1961).
20 Schove, D. J., *J. Br. astron. Assoc.*, **lviii**, 183 (1948).
21 Emerson, E., *Comet Lore*, 34, New York, 1910.
22 Chambers, G. F., *Handbook of Descriptive Astronomy*, 375, Oxford, 1877.
23 Wen Shion Tsu, *Popular Astronomy*, **xlii**, 191 (1934).
24 Schove, D. J., *op. cit.* (ref. 20), 180.
25 Schove, D. J., *ibid.*, 181.
26 Schove, D. J., *J. Br. astron. Assoc.*, **lxvi**, 138 (1956).
27 Chambers, G. F., *op. cit.* (ref. 22), 374.
28 Ho Peng Yoke, *op. cit.*, 142.
29 Norling, G., *Actes du VII^e congrès international d'histoire des sciences*, 458, Paris, 1953.
30 Ho Peng Yoke, *op. cit.*, 141.
31 Chambers, G. F., *The Story of the Comets*, 242, Oxford, 1909.
32 Olivier, C. P., *Comets*, 2, Baltimore, 1930.
33 Herschel, J., *Mon. Not. R. astron. Soc.*, **iv**, 25 (1836).
34 Bickerman, E. J., *Chronology of the Ancient World*, 46, London, 1968.
35 Bickerman, E. J., *ibid.*, 80.