1975AJ.....80..460K

Thirteenth satellite of Jupiter

C. T. Kowal

Hale Observatories, Carnegie Institute of Washington, California Institute of Technology, Pasadena, California

K. Aksnes and B. G. Marsden

Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory, Cambridge, Massachusetts

E. Roemer

Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona

(Received 5 March 1975)

The discovery, observations, and attempts to determine the orbit of Jupiter XIII are described. It is found that the orbit is very similar to the orbits of Jupiter VI, VII, and X. An ephemeris is provided for the 1975 opposition.

THE most extensive search hitherto for new satellites of Jupiter has been that by Nicholson (1939). That search, made with the 254-cm reflector at Mount Wilson in July–August 1938, covered a region extending 3° to the east and west of Jupiter and 1°.25 to the north and south. Kuiper (1961) judged the limiting photographic magnitude to have been about 19.5, and while the degree of completeness of the search is hard to estimate, it can be noted that this limit is close to the magnitude of satellite XII, which escaped detection for another 13 years (Nicholson 1951; Harris 1961).

With the help of modern techniques, it is reasonable to search for satellites that are considerably fainter than Nicholson's limit, and after a few initial experiments using different emulsions, one of us (C. T. K.) obtained a set of excellent exposures of the region around Jupiter on three consecutive nights in September 1974 with the 122-cm Schmidt telescope at Palomar Mountain. The plates were 120-min exposures on baked Kodak IIIa-J emulsion with a Wratten 4 filter. The telescope was guided to follow the motion of Jupiter, which was situated near the center of the 6°×6° field. Jupiter was then about one week past opposition, and the faintest images that would have been detectable on each plate for an object sharing Jupiter's motion were of magnitude about 22 (in a system that corresponds to something between the V and B scales but closer to the former).

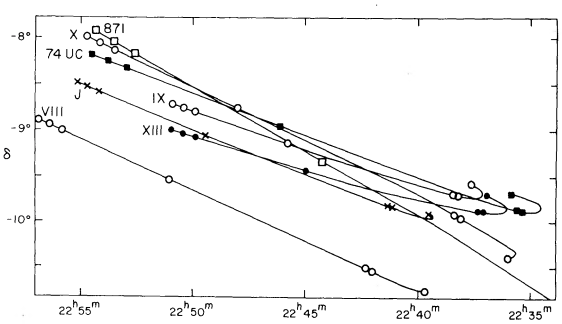

FIG. 1. A plot of right ascension α versus declination δ (equinox 1950.0), showing part of the retrograde loops for Jupiter (J), satellites VIII, IX, X, and XIII, and the minor planets (871) Amneris and 1974 UC. The points on the curves correspond to the seven nights on which the first eight reported observations of Jupiter XIII were made: 11, 12, 13, and 23 Sept. 1974; 17 and 18 Oct.; and 9 Nov.

During the course of blinking the plates on 14 September, a suspect satellite was discovered (Kowal 1974a). Of magnitude about 20, it was located some 70 arcmin to the west and south of Jupiter. Satellite IX could be identified 20 arcmin due north of the new object, and satellite XII was about 15 arcmin to the west. Even a casual glance at Fig. 1 shows that the motion of the new object (labeled XIII) during 11–13 September was indeed very similar to that of Jupiter (labeled J); satellite XII is not shown, but satellite IX, and also satellite VIII, had very similar motions too [where for the purpose of preparing this illustration the positions of these satellites were taken from the ephemerides by Herget (1968)], whereas satellite X, and particularly the two minor planets (871) Amneris and 1974 UC, were moving rather more rapidly. There thus seemed good reason to believe that the new object might be a satellite—and, perhaps, that it was a member of the outer group having retrograde orbits about Jupiter.

Accurate measurement of the three plates showed that the object's motion during 11–13 September differed by only 0".4 from a great circle, and since this was less than the presumed accuracy of each of the measurements, the orbit was completely indeterminate. In order to aid observers, however, a brief ephemeris was provided (Aksnes and Marsden 1974a), this having been derived from unpublished orbital elements resembling those of satellites VIII, IX, XI, and XII. The possibility that the object had a direct jovicentric orbit could certainly not be ruled out, and it was also possible to satisfy the three observations with heliocentric orbits. The fact that none of these heliocentric orbits could have eccentricity $e \lesssim 0.4$ did seem to make it rather unlikely that the object was a minor planet, although it could not be excluded that the object had, for example, an eccentric orbit in 2:1 mean-motion

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1975AJ.....80..460K

TABLE I. Orbits from observations to 23 September.

Orbit[a]	H		D		R	
T	1973 Sept. 6.7		1974 Aug. 18.5		1974 Aug. 18.5	
ω	256°.6		312°.5		312°.4	
Ω	358.0		254.9		242.9	
i	4.4		22.4		155.0	
e	1.0		0.314		0.350	
a	(q=2.344)		0.111		0.116	
Residuals	$\Delta\alpha \cos\delta$	$\Delta\delta$	$\Delta\alpha \cos\delta$	$\Delta\delta$	$\Delta\alpha \cos\delta$	$\Delta\delta$
Sept. 11.28	−0″.8	+0″.2	−0″.2	−0″.5	+4″.3	+0″.9
12.26	+1.2	+0.6	+1.3	+0.7	+0.8	+0.5
13.37	−0.4	−0.9	−1.2	−0.2	−6.2	−1.7
23.31	+1.3	0.0	+1.4	−0.1	+1.8	0.0
23.34	−1.4	+0.2	−1.3	+0.1	−0.8	+0.2

[a] For orbit H, T is the time of perihelion passage (and q is the perihelion distance); for orbits D and R, T is the time of perijove passage. The angular elements ω, Ω, and i are referred to the ecliptic of 1950.0 in each case.

resonance with Jupiter, like the minor planets (1362) Griqua, 1949 HC, and 1973 SE. There remained the possibility that the object was a comet, but although comets are sometimes completely stellar in appearance, such objects are rather rare (Roemer 1975).

Although the Moon was already at first quarter, a pair of 1½-min exposures (obtained with the use of an image tube attached to the Steward Observatory's 229-cm reflector on Kitt Peak) was—most fortunately—secured of the new object on 23 September. The semi-accurately scaled positions (Roemer *et al.* 1974) showed that there was by then a departure of 9 arcsec from great-circle motion. The five available observations could still be satisfied by a parabolic orbit about the Sun—the orbital elements and the residuals for this solution are shown in the column headed H in Table I—but it was not possible to fit a heliocentric elliptical orbit of semimajor axis $a \lesssim 6$ AU. General solutions for a jovicentric orbit failed, but particular least-square fits were made by fixing a and e and solving only for four orbital elements. Two representative jovicentric solutions are included in Table I, and it can be seen that whereas the residuals of the direct orbit (column D) are comparable to those of the heliocentric parabola, the trend in the first three right-ascension residuals of the retrograde orbit (column R) suggested that this solution was unacceptable. (Of course, the 23 September observations were obtained with the use of an image tube the astrometric properties of which were unexplored, and in any case the positions were not fully accurate measurements; however, the residuals of the two observations were mutually very consistent.) It thus seemed likely that the object was a member of the "middle" group of Jovian satellites (consisting hitherto of satellites VI, VII, and X), and although the orbital elements in column D of Table I were still judged to be too hypothetical to warrant their publication at the time, they were utilized for the continuation of the published ephemeris (Aksnes and Marsden 1974b).

At the October dark run the only immediately obvious observations of the new object were again obtained with the 122-cm Schmidt telescope (Kowal 1974b). Since the plates—taken on 17 and 18 October—were very dark, they were measured only semiaccurately, but the resulting positions showed that the departure from great-circle motion had now increased to 160 arcsec, and the heliocentric solutions were in trouble. The best fit was given by a hyperbola, but even in this case the October right-ascension residuals were unsatisfactory (see column H of Table II): the object was by then some six weeks past opposition and had slowed down in its apparent retrograde motion (Fig. 1), but if it had really had a heliocentric orbit, the motion would not have slowed down so sharply. It was still not possible to solve for all six elements of the jovicentric orbit, and solutions were first made with e fixed, but later with the time of perijove passage T fixed instead. One of the most satisfactory solutions (Aksnes 1974a), not surprisingly a direct orbit, is given in column D of Table II. Column R shows the result of attempting to force a retrograde orbit, which by then was obviously completely unsatisfactory.

A single observation was obtained with the 229-cm reflector at Kitt Peak on 9 November (Roemer 1974). Fog prevented a second plate from being taken, but since the object had by this time resumed its apparent direct motion, the 60-min exposure was a rather crucial one. On the Kodak 103a-O plate the object appears at B magnitude about 21.2. A heliocentric solution from all eight observations failed dramatically, giving residuals of well over 1 arcmin. The departure from great-circle motion was almost 12 arcmin, and now, for the first time, it proved possible to do a complete differential correction for all six elements of the jovicentric orbit (Aksnes 1974b). Allowance was made for the solar perturbations; perturbations by Saturn and the Earth were included too, the total accumulation over the two-month interval since the satellite's discovery amounting to some 20 arcsec. The result is given in Table III.

TABLE II. Orbits from observations to 18 October.

Orbit	H		D		R	
T	1973 Sept. 29.9		1974 July 16.9		1974 Aug. 11.4	
ω	254°.1		268°.0		306°.1	
Ω	356.9		249.2		245.3	
i	4.7		24.9		154.0	
e	1.187		0.105		0.150	
a	−11.1		0.083		0.091	
Residuals	$\Delta\alpha \cos\delta$	$\Delta\delta$	$\Delta\alpha \cos\delta$	$\Delta\delta$	$\Delta\alpha \cos\delta$	$\Delta\delta$
Sept. 11.28	−1″.6	−0″.5	0″.0	−0″.5	+29″.5	+6″.5
12.26	+1.5	+0.1	+1.2	+0.6	+20.0	+4.6
13.37	+0.8	−1.0	−1.4	−0.2	+6.0	+0.7
23.31	+1.0	+1.0	+1.5	0.0	−50.6	−13.6
23.34	−1.7	+1.2	−1.2	+0.2	−53.3	−13.4
Oct. 17.23	−3.4	−0.6	−0.8	−0.5	+14.5	+3.2
18.24	+3.4	−0.2	+0.8	+0.4	+21.4	+4.9

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1975AJ.....80..460K

TABLE III. Orbit from observations to 9 November.

Epoch[a]	1974 Sept. 10.0 ET	
T	1974 June 27.777 ET	
ω	205°706	1950.0
Ω	250.080	1950.0
i	28.767	1950.0
q	0.05155 AU	
e	0.24443	
a	0.06822 AU	
$n°$	1.709	
P	210.6 days	

Residuals	$\Delta\alpha \cos\delta$	$\Delta\delta$
Sept. 11.28	+0″1	0″0
12.26	+1.1	+1.0
13.37	−1.7	0.0
23.31	+1.6	−0.3
23.34	−1.1	−0.1
Oct. 17.23	−0.3	−1.1
18.24	+0.3	−0.4
Nov. 9.23	−0.1	+1.3

[a] q is the perijove distance and $n°$ the mean daily motion (in degrees).

TABLE V. Final orbit and residuals.

Epoch	1974 Sept. 10.0 ET	
T	1974 June 21.9759± 0.2598 (m. e.) ET	
ω	217°1655±0°2922	1950.0
Ω	248.2215±0.1242	1950.0
i	26.7207±0.0487	1950.0
q	0.063338±0.000375 AU	
e	0.147149±0.003006	
a	0.074266±0.000701 AU	
$n°$	1.5048 ±0.0213	
P	239.24 ±3.39 days	

Residuals	$\Delta\alpha \cos\delta$	$\Delta\delta$
Sept. 11.28	+0″2	−0″7
12.26	+1.5	+0.4
13.37	−1.0	−0.3
23.31[a]	−0.4	−0.5
23.34[a]	−0.7	−0.2
Oct. 17.23[a]	−0.5	+1.7
18.24[a]	−0.3	−0.8
21.16	+1.0	+0.6
Nov. 9.23	+0.5	0.0
Dec. 12.16	−0.4	−1.1

[a] It should be noted that these residuals refer to accurate measurements, which differ from those used in the orbits in Tables I, II, and III by up to 7 arcsec.

A final attempt to photograph the new satellite was made with the 122-cm Schmidt on 12 December, by which time Jupiter was more than three months past opposition. The satellite was then only 25 arcmin from Jupiter, and an opaque mask was placed in front of the filter to eliminate reflections of Jupiter from the filter. An image was found and measured (Kowal 1975). Although attempts to include this observation in the solution for the orbit suggested that it did indeed refer to the satellite, the resulting elements differed rather substantially from those in Table III, and the residuals of the semiaccurate 23 September and 17–18 October observations increased to several arcsec, which was somewhat surprising in view of the small residuals in that table. With the intermediary of a Kodak 103a-D plate, from which the positions of faint stars very close to the satellite could be determined, it was possible to obtain improved positions from the October IIIa-J plates, and these differed by 6–7 arcsec from the earlier figures (mainly in right ascension). Although relatively small, these differences (observed from the Earth) nevertheless amount to as much as 6 arcmin jovicentrically, which means a substantial change in the derived orbital elements of the satellite. Accurate measurement of the 23 September image-tube exposures was complicated by the necessity of taping the circular plates to an 8×10 backing glass in order to secure them in the measuring engine; furthermore, the images of each of the (only) three reference stars were more than 1 mm in diameter, and there were signs of a magnitude-related astrometric error between the images of the stars and the satellite.

TABLE IV. Observations.

1974 UT	α_{1950}	δ_{1950}	Location
Sept. 11.28194	22ʰ50ᵐ57ˢ28	−8°59′27″2	Palomar
12.26042	22 50 26.09	−9 01 52.9	Palomar
13.37083	22 49 50.68	−9 04 37.3	Palomar
23.30968	22 44 58.02	−9 26 20.3	Kitt Peak
23.33772	22 44 57.22	−9 26 23.1	Kitt Peak
Oct. 17.23472	22 37 17.72	−9 53 44.8	Palomar
18.24236	22 37 07.73	−9 54 04.9	Palomar
21.16210	22 36 43.60	−9 54 30.1	Kitt Peak
Nov. 9.23420	22 36 58.36	−9 42 50.3	Kitt Peak
Dec. 12.16458	22 48 18.21	−8 29 41.2	Palomar

On subsequent careful inspection of a 31-min exposure (stopped prematurely by the loss of the guide star in clouds) with the 229-cm reflector on 21 October, it was possible to identify and measure a very faint image that appeared at precisely the spot calculated for Jupiter XIII; on the other hand, a 90-min exposure on 16 November with the 154-cm reflector at the Catalina Station of the Lunar and Planetary Laboratory did not yield any measurable image of the satellite. For convenience, we list all ten accurately measured positions together in Table IV.

The final solution for the orbit, based now on the ten accurate positions, is given in Table V. The residuals, even for the image-tube observations, are extremely satisfactory. The orbit is now seen to be very similar to the orbits of satellites VI, VII, and X, which have values of a between 0.002 and 0.004 AU larger (or periods P between 10 and 20 days longer) and rather comparable values of e and i.

Figure 2 shows the apparent motion of satellite XIII with respect to Jupiter, and an ephemeris is given in Table VI for an interval of several months on each side of the opposition in October 1975. The orbital elements in Table V were used as the basis of these calculations, and while there must still be some uncertainty (particularly in P), this should not affect the ephemeris in 1975 by more than a few minutes of arc. Around the

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1975AJ.....80..460K

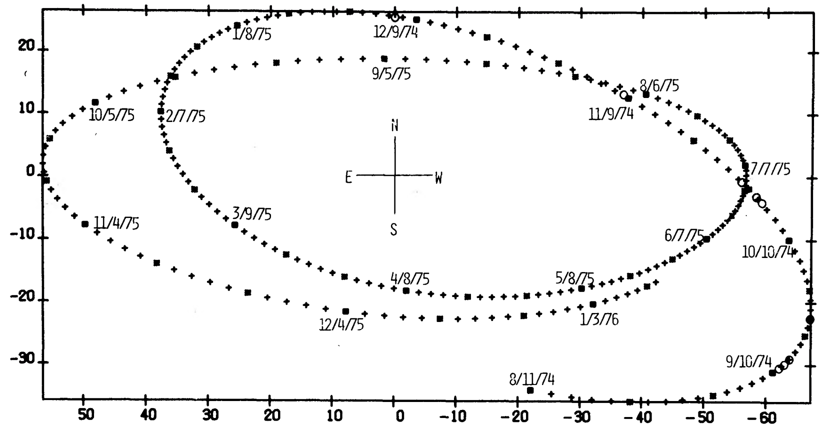

FIG. 2. Offsets of Jupiter XIII from Jupiter (in arcmin), 11 Aug. 1974 to 15 Jan. 1976. Crosses (+) are at intervals of 2 days and squares (■) at 10 days. The nine nights of the observations are marked by circles (○).

time of new moon in early July 1975 the satellite will be just moving in from apojove and favorably placed for observation near a maximum elongation, some 55 arcmin west of Jupiter. At the August new moon it will have relative position and motion comparable to those at the time of the Kitt Peak observation in November 1974. Observations in early September 1975 will be very difficult because the satellite will be only 19 arcmin due north of Jupiter. Observations during the October and November dark runs will find the satellite near perijove, but it will also be near greatest eastern elongation, 50 arcmin and more from Jupiter. The satellite will pass about 22 arcmin south of the planet at the beginning of December, but by the following new moon it will be well separated to the southwest of Jupiter and approaching apojove again.

Figure 2 also illustrates that the discovery of Jupiter XIII was made in September 1974 under very favorable circumstances. The satellite was then near its maximum separation from Jupiter, and the relative motion was very small. It is unlikely that the satellite would have been discovered during the October observing run. It was on that occasion that 1974 UC was discovered. The motion of this object was then practically identical with that of Jupiter (see Fig. 1), but since that motion was so much smaller than in September, this is not particularly surprising; and although 1974 UC was initially noted as a possible candidate for yet another satellite of Jupiter, it soon became clear that it was a rather ordinary minor planet having $a=3.13$ AU, $e=0.12$. Several identifications of it have now been made between 1934 and 1969 (Bardwell 1975).

The photographic mean opposition magnitude of Jupiter XIII is evidently close to 21, or about $1\frac{1}{2}$ mag fainter than Jupiter XII. Further searches with the 122-cm Schmidt and the Kodak IIIa-J emulsion/Wratten 4 filter combination will undoubtedly reveal further satellites. We judge that for the next few years there is about an even chance that each opposition could produce a new satellite comparable in brightness to Jupiter XIII, provided that such a satellite happened to be reasonably near its extreme elongation east or west of Jupiter. Discoveries are likely to be made within a very few weeks of opposition—and it should be noted that Jupiter's 1975 opposition is a perihelic one. The problem of obtaining enough observations for an adequate orbit determination for a new satellite cannot be overestimated, and although the use of an image tube seems to have been successful in the case of Jupiter XIII, there were difficulties that do not arise in the case of direct exposures. Close cooperation and communication among those making the observations and those computing the orbits is essential, and more participation by users of large telescopes would be appreciated.

TABLE VI. Ephemeris.

1975/76 (0^hET)	α_{1950}	δ_{1950}	$\Delta\alpha$[a]	$\Delta\delta$[a]	Δ	r
June 17	$1^h09^m.08$	$+6°16'.9$	$-3^m.64$	$-6'.1$	5.273	0.085
27	1 14.60	+6 53.0	−3.79	−2.1	5.143	0.084
July 7	1 19.45	+7 23.7	−3.79	+1.9	5.008	0.084
17	1 23.54	+7 48.4	−3.63	+6.0	4.869	0.082
27	1 26.77	+8 06.4	−3.28	+9.8	4.730	0.080
Aug. 6	1 29.07	+8 17.3	−2.73	+13.3	4.592	0.078
16	1 30.37	+8 20.4	−1.96	+16.1	4.460	0.075
26	1 30.63	+8 15.6	−0.99	+18.1	4.337	0.073
Sept. 5	1 29.81	+8 02.6	+0.12	+18.9	4.225	0.070
15	1 27.91	+7 41.8	+1.29	+18.2	4.129	0.068
25	1 25.00	+7 14.1	+2.38	+15.8	4.051	0.066
Oct. 5	1 21.19	+6 41.1	+3.23	+11.6	3.996	0.065
15	1 16.67	+6 05.1	+3.71	+5.8	3.968	0.065
25	1 11.76	+5 29.1	+3.74	−0.9	3.968	0.066
Nov. 4	1 06.83	+4 56.0	+3.33	−7.8	4.001	0.067
14	1 02.31	+4 28.8	+2.56	−13.9	4.064	0.069
24	0 58.59	+4 09.8	+1.58	−18.7	4.157	0.071
Dec. 4	0 55.99	+4 00.3	+0.52	−21.7	4.275	0.074
14	0 54.69	+4 00.8	−0.50	−22.8	4.414	0.076
24	0 54.79	+4 11.0	−1.40	−22.2	4.568	0.079
Jan. 3	0 56.28	+4 30.1	−2.15	−20.3	4.732	0.081
13	0 59.09	+4 57.3	−2.74	−17.4	4.900	0.083

[a] $\Delta\alpha$ and $\Delta\delta$ are the offsets from Jupiter; Δ and r are the geocentric and jovicentric distances (in AU).

ACKNOWLEDGMENTS

This study was supported in part under NSF grant NSF-4 MPS75-00555 (C.T.K.), and NASA grants NGR 09-015-213 (K.A. and B.G.M.) and NGL 03-002-122 (E.R.).

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1975AJ.....80..460K

REFERENCES

Aksnes, K. (1974a). IAU Circ. No. 2711.
Aksnes, K. (1974b). IAU Circ. No. 2732.
Aksnes, K., and Marsden, B. G. (1974a). IAU Circ. No. 2702.
Aksnes, K., and Marsden, B. G. (1974b). IAU Circ. No. 2703.
Bardwell, C. M. (1975). Private communication.
Harris, D. L. (1961). In *Planets and Satellites*, Vol. 3 of *The Solar System*, edited by G. P. Kuiper and B. M. Middlehurst (Univ. Chicago P., Chicago), p. 272.
Herget, P. (1968). Publ. Cincinnati Obs. No. 23.
Kowal, C. T. (1974a). IAU Circ. No. 2702.
Kowal, C. T. (1974b). IAU Circ. No. 2711.
Kowal, C. T. (1975). IAU Circ. No. 2742.
Kuiper, G. P. (1961). In *Planets and Satellites*, Vol. 3 of *The Solar System*, edited by G. P. Kuiper and B. M. Middlehurst (Univ. Chicago P., Chicago), p. 575.
Nicholson, S. B. (1939). Astron. J. **48**, 129.
Nicholson, S. B. (1951). Publ. Astron. Soc. Pac. **63**, 297.
Roemer, E. (1974). IAU Circ. No. 2732.
Roemer, E. (1975). IAU Colloq. No. 25. To be published.
Roemer, E., McCarthy, C., Weymann, R., Cromwell, R., and McCallister, R. (1974). IAU Circ. No. 2703.

© American Astronomical Society • Provided by the NASA Astrophysics Data System