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I am submitting herewith a thesis written by Anthony Thomas Lyons entitled "An Analysis of the Perturbations on Chiron's Orbit due to the Major Planets." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Engineering Science.

T. Conley Powell, Major Professor

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AN ANALYSIS OF THE PERTURBATIONS ON CHIRON'S ORBIT DUE TO THE MAJOR PLANETS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Anthony Thomas Lyons

December 1978

1372897

ABSTRACT

Chiron is a small object whose orbit is between the orbits of Saturn and Uranus. The purpose of this study was to determine what effect the gravitational forces of the four major planets have had on Chiron's orbit. The non-perturbed position and velocity of Chiron were determined analytically from initial orbital elements. The perturbations in position and velocity were found by numerical integration. Chiron's actual position and velocity were obtained by adding position and velocity perturbations and the non-perturbed position and velocity. New orbital elements were then found analytically from the actual position and velocity. These new elements were recalculated at regular intervals over a 24,000 year period. Both past and future calculations were done. It was found that Chiron has repeatedly passed close to Saturn and has gone through significant changes in its orbit as a result.

These close approaches introduce considerable numerical errors. However, additional calculations have shown, at least for epochs prior to 2,000 years ago, uncertainties in Chiron's present orbital elements have much larger effects than any numerical errors.

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LIST OF SYMBOLS

SYMBOL	
E	eccentric anomaly
e	eccentricity
f	true anomaly
h	angular momentum per unit mass
i	inclination
K	gravitational constant
M	mean anomaly
m	mass
p	semilatus rectum
r	position
t	time
u	argument of latitude
v	velocity
δr	perturbation in position
δv	perturbation in velocity
Ω	longitude of ascending node
ω	argument of pericenter

INTRODUCTION

Chiron was first discovered in November 1977 by Charles Kowal of Hale Observatories. It was found to be a slowly moving object located between the orbits of Saturn and Uranus. While the exact nature of this object remains a matter of conjecture, a search of photographs by astronomers has uncovered seventeen different observations of Chiron. The oldest observation found so far dates back to 1969. From these observations a set of orbital elements has been calculated which fits all seventeen observations to within two seconds of arc. These orbital elements were published in several astronomical publications, including Sky and Telescope (1) magazine, and are given in Table 1.

Chiron's aphelion is 18.9 astronomical units, and its perihelion is 8.5 a.u. Such an orbit enables Chiron to pass within two a.u. of both Saturn and Uranus within one revolution if the two planets are positioned properly. Under such circumstances it appears to be possible that the gravitational attractions of the major planets Jupiter, Saturn, Uranus, and Neptune have had a significant effect on Chiron's orbit. From Chiron's present orbital elements the author has attempted to determine what effect the major planets have had on Chiron's orbit. Calculations were also done to determine if Chiron has passed closely by any of the major planets.

TABLE 1

INITIAL ORBITAL ELEMENTS OF CHIRON

Time of pericenter passage	Feb. 13.170, 1996
Argument of pericenter	$339^{o}.005$
Longitude of ascending node	$208^{o}.716$
Inclination	$6^{o}.923$
Eccentricity	0.3786
Semimajor Axis	13.6991 a.u.

CHAPTER I

ANALYSIS

The method of calculation used for the determination of Chiron's orbit is an iterative one, as illustrated in Figure 1. From initial orbital elements, non-perturbed positions of Chiron and the four major planets are found for the first time step. From these positions, the perturbations in Chiron's position and velocity are found by numerical integration. This process is repeated for subsequent time steps until the end of a 100 year interval of time. At the end of the 100 year interval, Chiron's non-perturbed velocity is found. The non-perturbed position and velocity of Chiron are added to the position and velocity perturbations to find Chiron's actual postion and velocity. From the actual position and velocity, a new set of orbital elements is found. The entire process is then repeated for the next 100 years.

The six orbital elements needed for Chiron and each of the four major planets are described in the next section. The elements of the major planets are available from standard references or from simple calculations from other elements. The elements of Chiron are available from the Sky and Telescope article (1) or from calculations based on those elements.

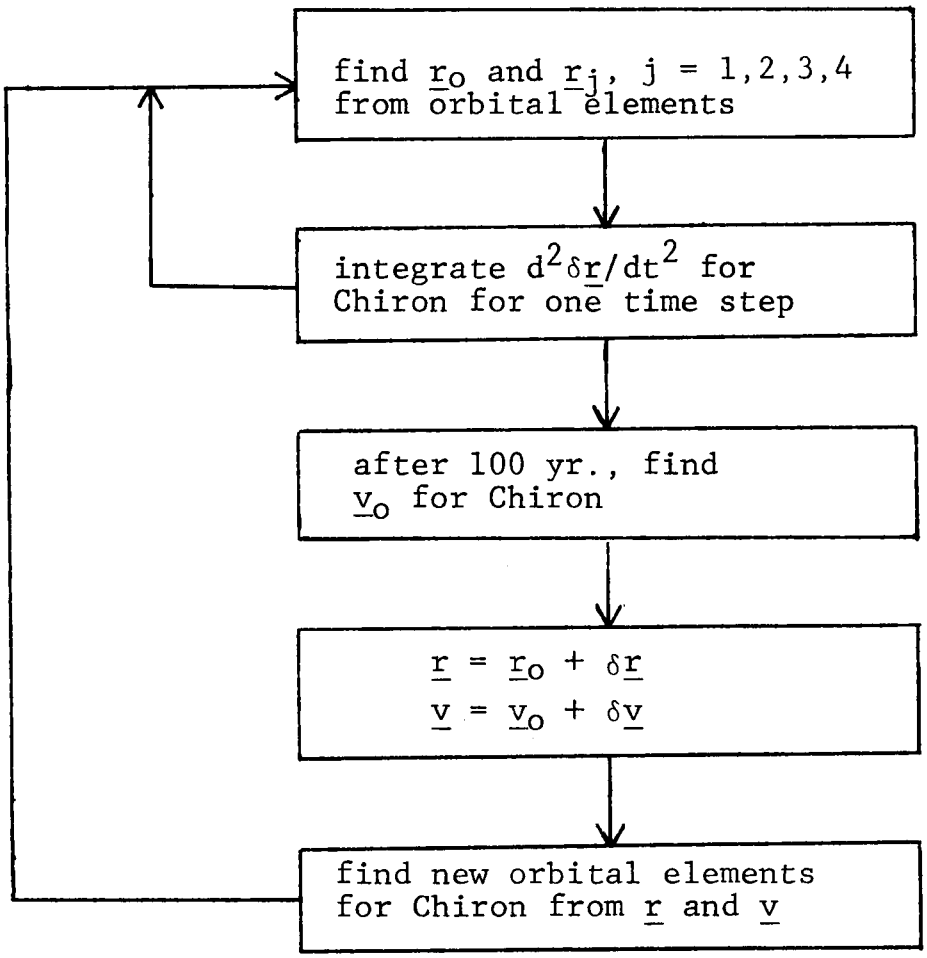

Figure 1. General Flow Diagram for Method Used in Calculating Orbit.

With the orbital elements in hand, it becomes possible to compute the positions of the five bodies in question from the orbit prediction method, described in the next section. Once the positions are known it is possible to calculate the perturbations in Chiron's position and velocity. This is done by use of Encke's equation, which is given by Brouwer and Clemence (2) as

$$d^2 \underline{r}/dt^2 = - (1 + m)(\underline{r}/|\underline{r}|^3 - \underline{r}_o/|\underline{r}_o|^3)$$
$$- \sum_{j=1}^{4} \mu^2 m_j \{(\underline{r} - \underline{r}_j)/|\underline{r} - r_j|^3 + \underline{r}_j/|\underline{r}_j|\}$$

where m is Chiron's mass (in solar masses), m_j is the mass of the jth planet, μ is a non-dimensionalized gravitational constant, $\underline{r}_o$ is Chiron's position calculated from the orbit prediction method, $\underline{r}_j$ is the position of the jth planet calculated by the same method, $\delta\underline{r}$ is the perturbation in Chiron's position, and $\underline{r}$ is given by

$$\underline{r} = \underline{r}_o + \delta\underline{r} \quad .$$

The initial value of the perturbation is zero. Chiron's mass is negligible, and the masses of the sun and the major planets were combined with the gravitational constant, μ, by

$$K = \mu^2 m \quad .$$

With these considerations, Encke's equation becomes

$$d^2\delta\underline{r}/dt^2 = -K\{(\underline{r}_o + \delta\underline{r})/|\underline{r}_o + \delta\underline{r}_o|^3 - \underline{r}_o/|\underline{r}_o|^3\}$$

$$- \sum_{j=1}^{4} K_j\{(\underline{r}_o + \delta\underline{r} - \underline{r}_j)/|\underline{r}_o + \delta\underline{r} - \underline{r}_j|^3 + \underline{r}_j/|\underline{r}_j|^3\}.$$

It should be noted that the original Encke method involves a numerical method for the evaluation of the right side of this equation. However, the use of a high-speed computer and double-precision arithmetic makes it possible to evaluate this expression directly.

Encke's equation was integrated by the use of a seventh order Runge-Kutta method developed by Fehlberg (4). This method simultaneously solves the differential equation by both the seventh and eighth order methods. The results of the two methods are then tested to determine if they agree within a user-specified tolerance. If agreement is not reached, the stepsize is decreased, and the previous step is repeated. The initial stepsize, specified by the user, is set at one tenth of a year for this particular integration.

The integration period is one hundred years. Therefore, the results of the integration are the perturbations in Chiron's position and velocity, due to the major planets, after one hundred years. Chiron's actual position and velocity can then be found by adding the position and velocity perturbations to the non-perturbed position and velocity. It is then possible to calculate a new set of orbital elements for Chiron from the orbit

determination method, described in the section, Calculation of Orbital Elements from Position and Velocity. Once a new set of orbital elements is found, the integration-and-orbit-determination process is repeated for the next hundred years. The orbital elements of the major planets are assumed to be constant. While these elements are not constant, they do not change significantly during the interval of interest.

Determination of Position and Velocity from Orbital Elements

Given a set of orbital elements, it is possible to find the position and velocity of a body orbiting another body. The necessary orbital elements are

e	eccentricity
p	semilatus rectum
ω	argument of pericenter
Ω	longitude of the ascending node
i	inclination
M_o	mean anomaly at time t_o .

Also needed are K, the gravitational parameter of the body being orbited, and t, the time from t_o. Given these, the first step is to find a mean anomaly M, for time t from

$$M = M_o + (K/p^3)^{\frac{1}{2}}(1 - e^2)^{3/2}t \quad .$$

It is then necessary to find the eccentric anomaly E, from

$$M = E - e \sin E \quad .$$

Solution of this equation, of course, must be done numerically, and the Newton-Raphson method is recommended. Once it is solved, it is then possible to find the true anomaly f, from

$$f = 2 \tan^{-1}(\{(1 + E)/(1 - E)\}^{\frac{1}{2}} \tan \{E/2\}) \quad .$$

The radial and transverse components of the velocity are

$$v_r = (K/p)^{\frac{1}{2}} e \sin f$$

$$v_f = (1 + e \cos f)\, v_r/(e \sin f) \quad .$$

Given the above, it then becomes possible to find the x, y, and z components of the position and velocity in rectangular orbital coordinates from

$$r_{xo} = (p \cos f)/(1 + e \cos f)$$

$$r_{yo} = r_{xo} \tan f$$

$$r_{zo} = 0$$

$$v_{xo} = v_r \cos f - v_f \sin f$$

$$v_{yo} = v_r \sin f - v_f \cos f$$

$$v_{zo} = 0 \quad .$$

The transformation of the position components from rectangular orbital coordinates to rectangular ecliptic coordinates is accomplished by

$$\begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix} = T \begin{bmatrix} r_{xo} \\ r_{yo} \\ r_{zo} \end{bmatrix}$$

where T is a matrix given by

$$T = \begin{bmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{bmatrix}$$

and the individual elements of the matrix are

$$T_{11} = \cos \Omega \cos \omega - \cos i \sin \Omega \sin \omega$$

$$T_{12} = -\cos \Omega \sin \omega - \cos i \sin \Omega \cos \omega$$

$$T_{13} = \sin i \sin \Omega$$

$$T_{21} = \sin \Omega \cos \omega + \cos i \cos \Omega \sin \omega$$

$$T_{22} = -\sin \Omega \sin \omega + \cos i \cos \Omega \cos \omega$$

$$T_{23} = -\sin i \cos \Omega$$

$$T_{31} = \sin i \sin \omega$$

$$T_{32} = \sin i \cos \omega$$

$$T_{33} = \cos i \quad .$$

Calculation of Orbital Elements from Position and Velocity

Given the position and velocity vectors of a planet, it is possible to calculate a set of orbital elements for this planet. If the orbit is elliptic, the first step is to find the radial and transverse components of the planet's velocity from

$$v_r = \underline{r} \cdot \underline{v}/r$$

$$v_f = (v^2 - v_r^2)^{\frac{1}{2}} \quad .$$

The semilatus rectum p, eccentricity e, true anomaly f, and the orbital angular momentum per unit mass h, can then be found from

$$p = r^2 v_f^2/K$$

$$e = \{1 + (rv_f^2/K)(rv^2/K - 2)\}^{\frac{1}{2}}$$

$$f = 2 \tan^{-1}\{(rv_r v_f/K)/(\{1 + (rv_f^2/K)(rv^2/K - 2)\}^{\frac{1}{2}} + rv_f^2/K - 1\}$$

$$\underline{h} = \underline{r} \times \underline{v} \quad .$$

It then becomes possible to find the eccentric anomaly E, mean anomaly M_o and inclination i, from

$$E = 2 \tan^{-1}(\tan (f/2)\{(1 - e)/(1 + e)\}^{\frac{1}{2}})$$

$$M_o = E - e \sin E - (K/p^3)^{\frac{1}{2}}(1 - e^2)^{3/2}t$$

$$i = \cos^{-1}(h_z/h)$$

where t is the time at which the orbital elements are to be calculated, and h_z is the z component of the angular momentum. It then becomes possible to calculate the longitude of the ascending node Ω, which is

$$\Omega = 2 \tan^{-1}\{(h_x/h)/(\sin i - h_y/h)\} \quad .$$

One is then able to find the argument of latitude u, from

$$u = 2 \tan^{-1}\{(-r_x \sin \Omega + r_y \cos \Omega)/ (r + r_x \cos \Omega + r_y \sin \Omega) \cos i\}$$

$$\omega = u - f \quad .$$

For more information on this method and the method in the previous section, works by Escobal (3) and Powell (5) are recommended.

CHAPTER II

RESULTS

Most of the calculations were concerned with past variations in Chiron's orbital elements. For purposes of obtaining orbital elements of the major planets from the 1978 Nautical Almanac (6), and for purposes of calculation, the initial time, t_0, was taken arbitrarily as February 21, 1978. The unit of distance used was the astronomical unit (a.u.), the unit of time was the year, and angular measurements were in radians. Unless otherwise specified, these are the units used in the tables and figures of this paper. It should be noted that Figures 2 through 13 are grouped together by orbital element. For example, the variations in Chiron's eccentricity over the past 24,000 years are shown in Figure 2. The same variations for the next 24,000 years are shown in Figure 3. Likewise, even-numbered figures show variations in the past orbital elements, and odd-numbered figures show variations in future orbital elements.

As mentioned earlier (section 1), it is possible to specify an integration tolerance for the purpose of controlling the integration stepsize and minimizing the errors in integration. The graphs in Figures 2 through 13 and Table 2 are based on calculations in which the integration tolerance was 10^{-13}. Integration backward in

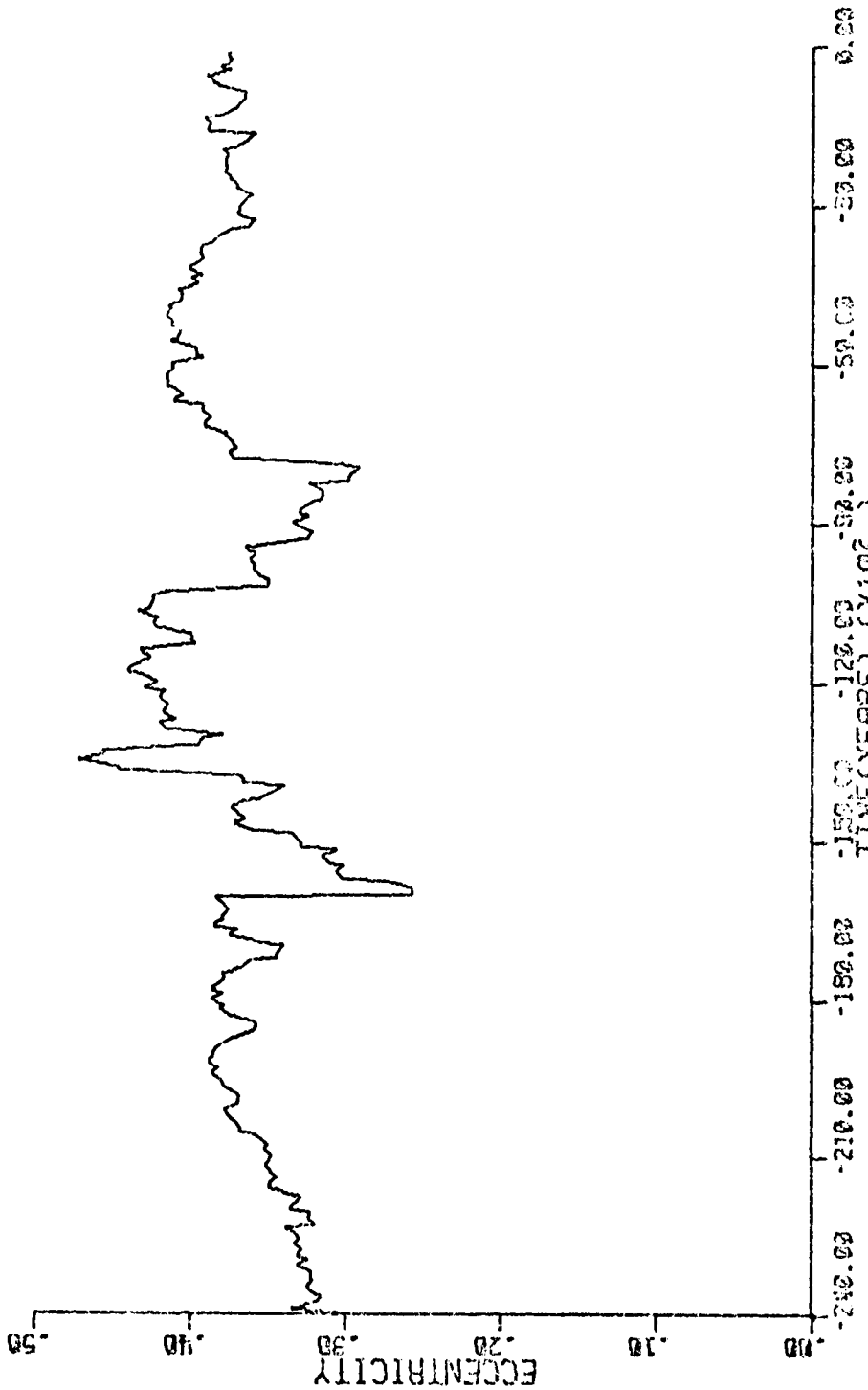

Figure 2. Variation in Chiron's Eccentricity for the Last 24,000 Years.

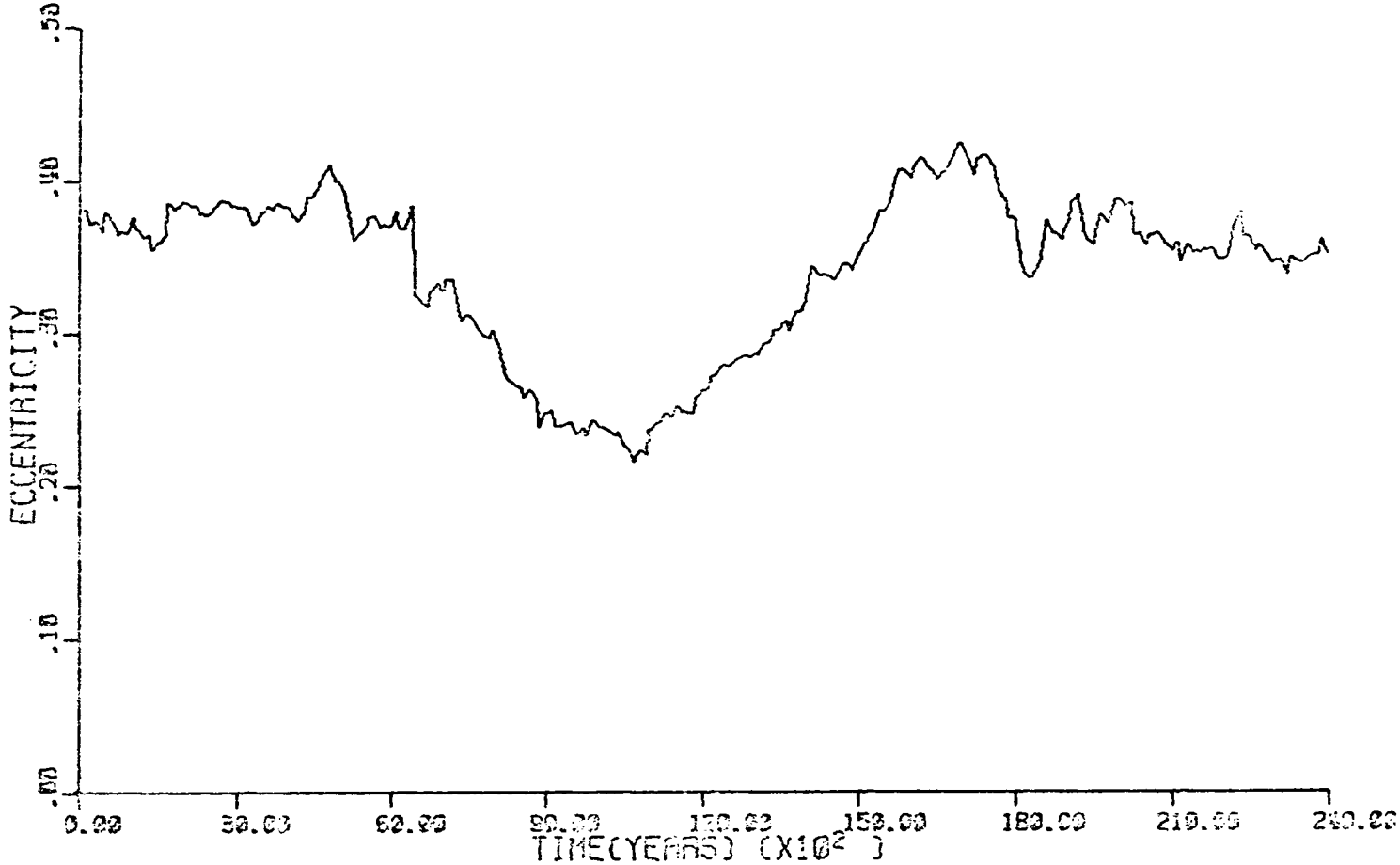

Figure 3. Variation in Chiron's Eccentricity for the Next 24,000 Years.

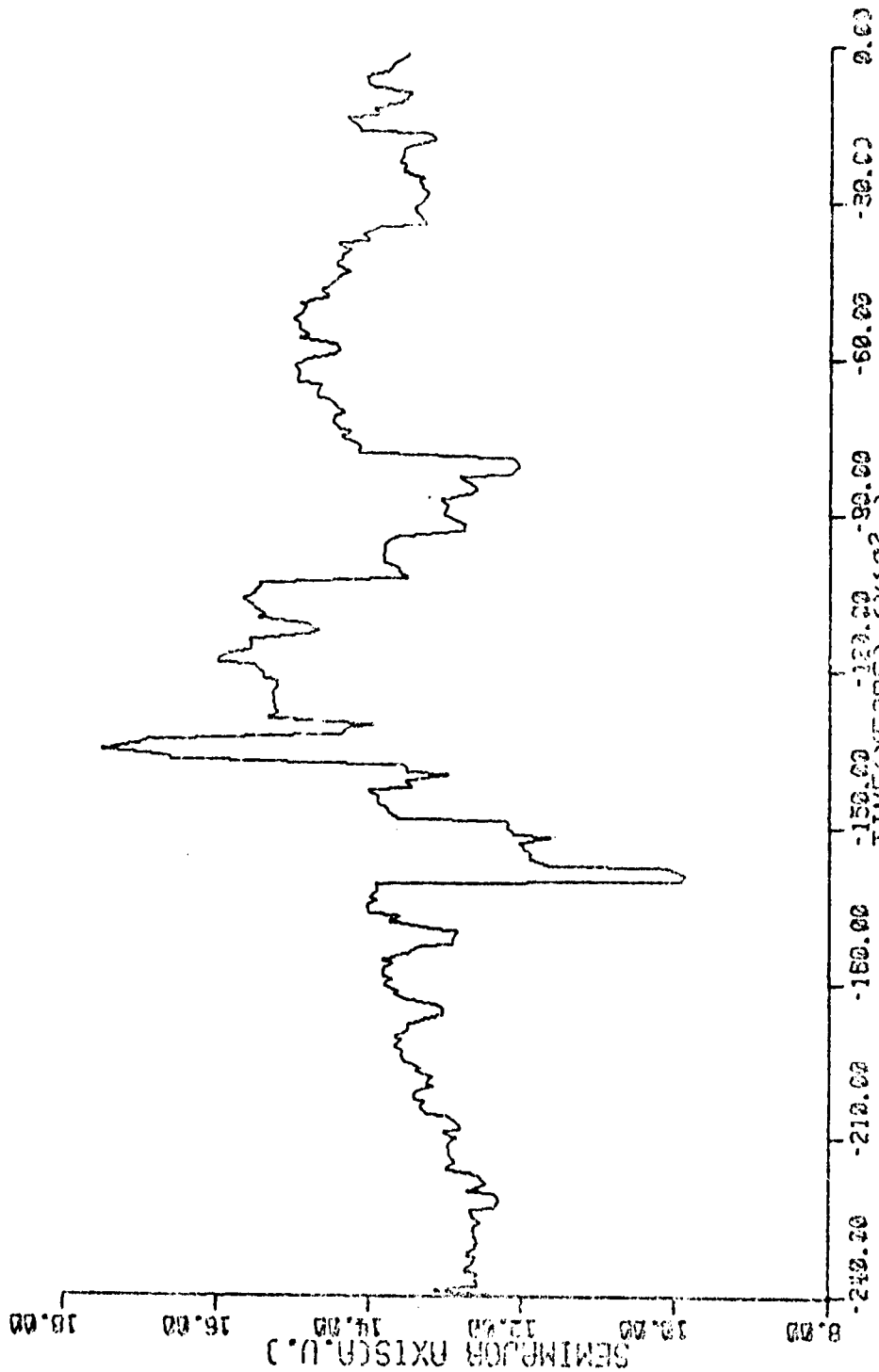

Figure 4. Variation in Chiron's Semimajor Axis for the Last 24,000 Years.

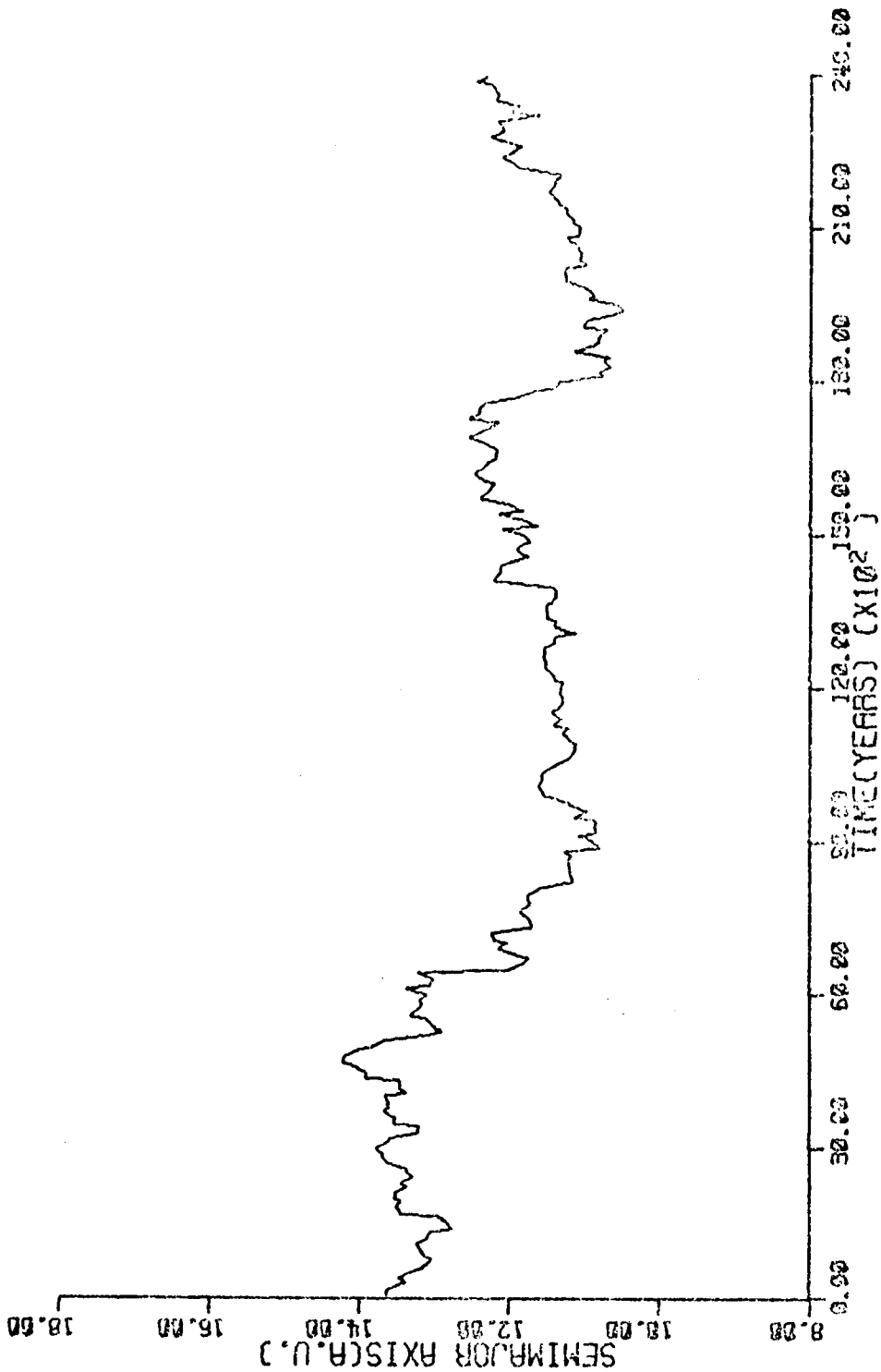

Figure 5. Variation in Chiron's Semimajor Axis for the Next 24,000 Years.

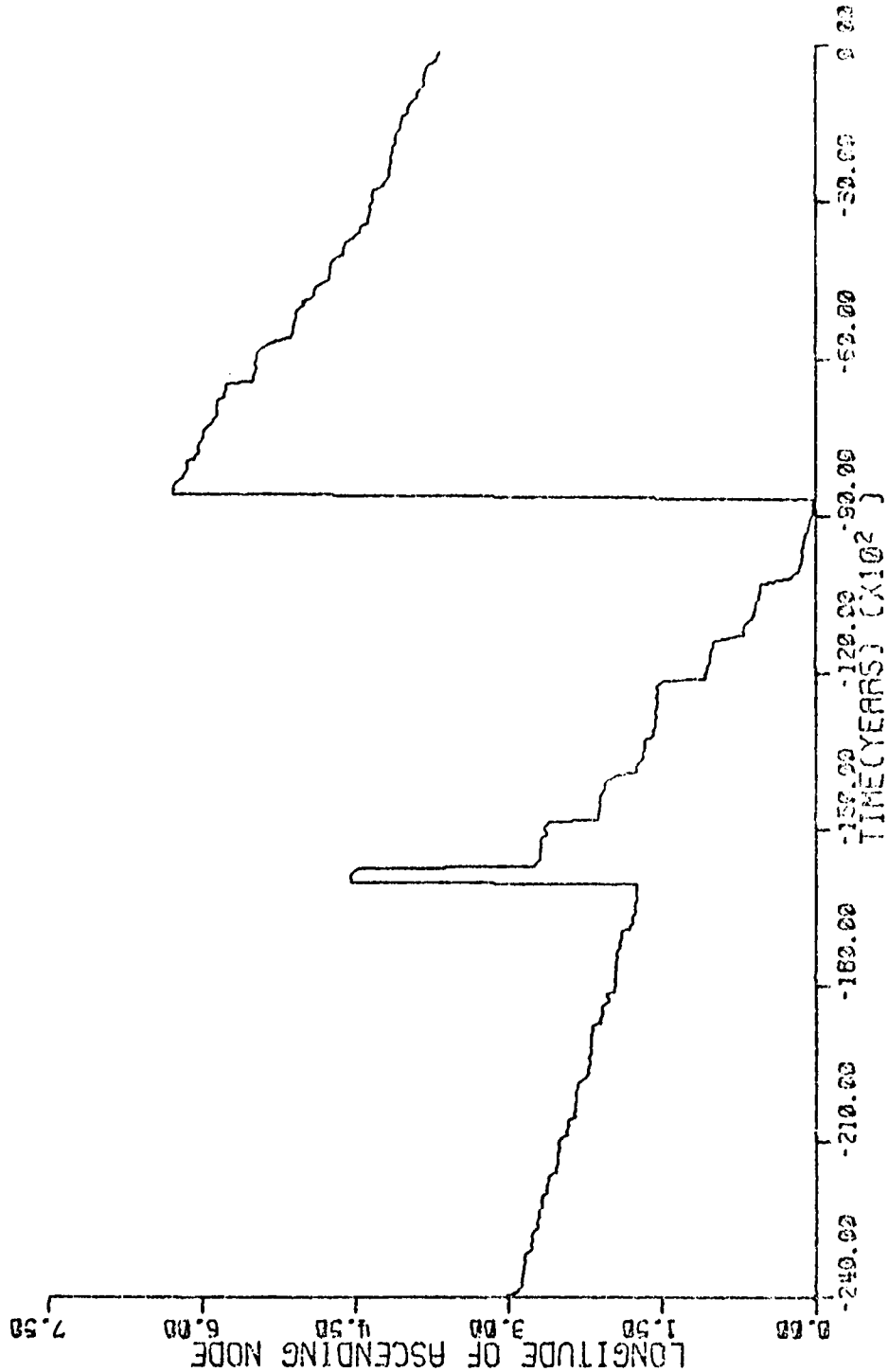

Figure 6. Variation in Chiron's Longitude of Ascending Node for the Last 24,000 Years.

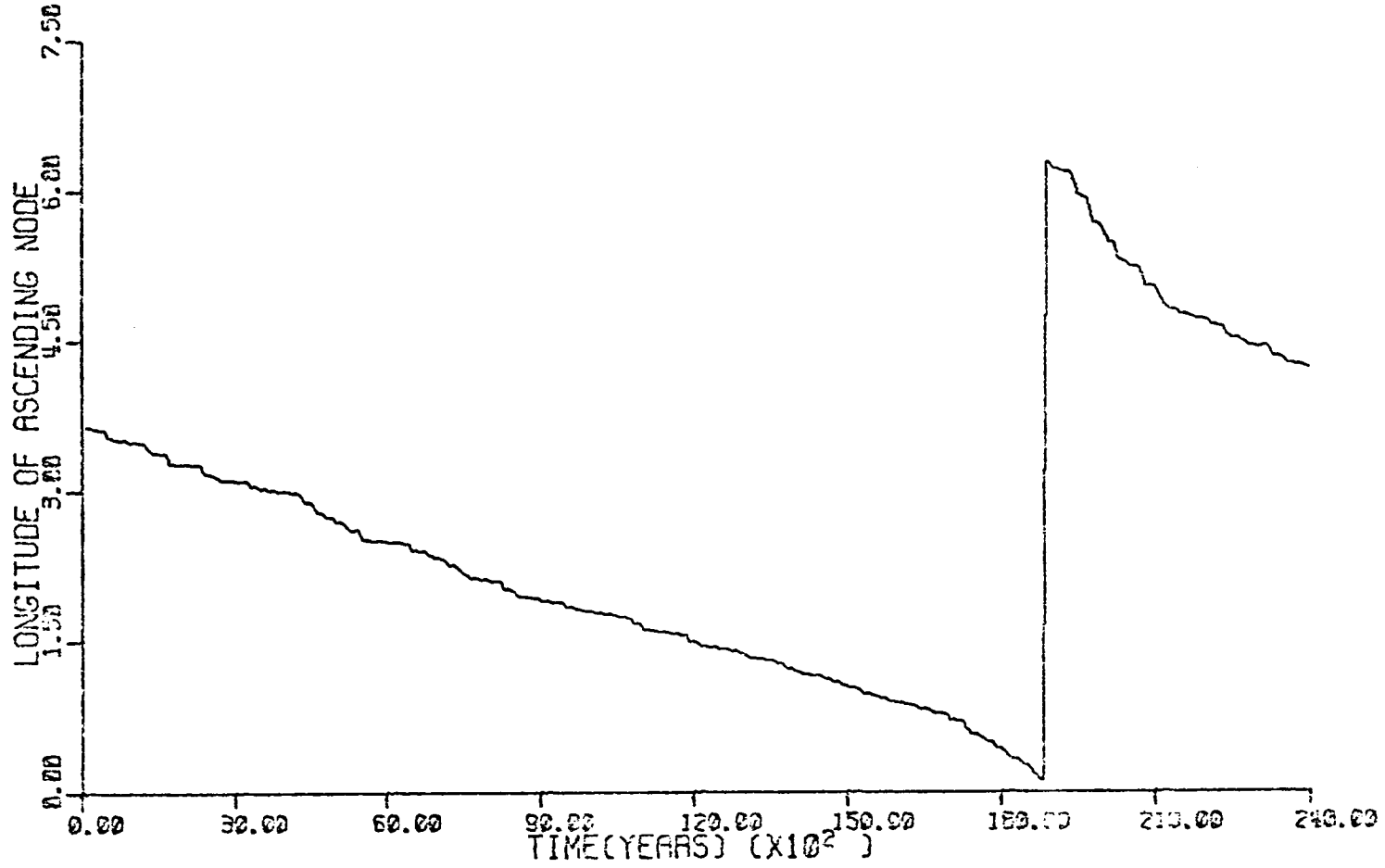

Figure 7. Variation in Chiron's Longitude of Ascending Node for the Next 24,000 Years.

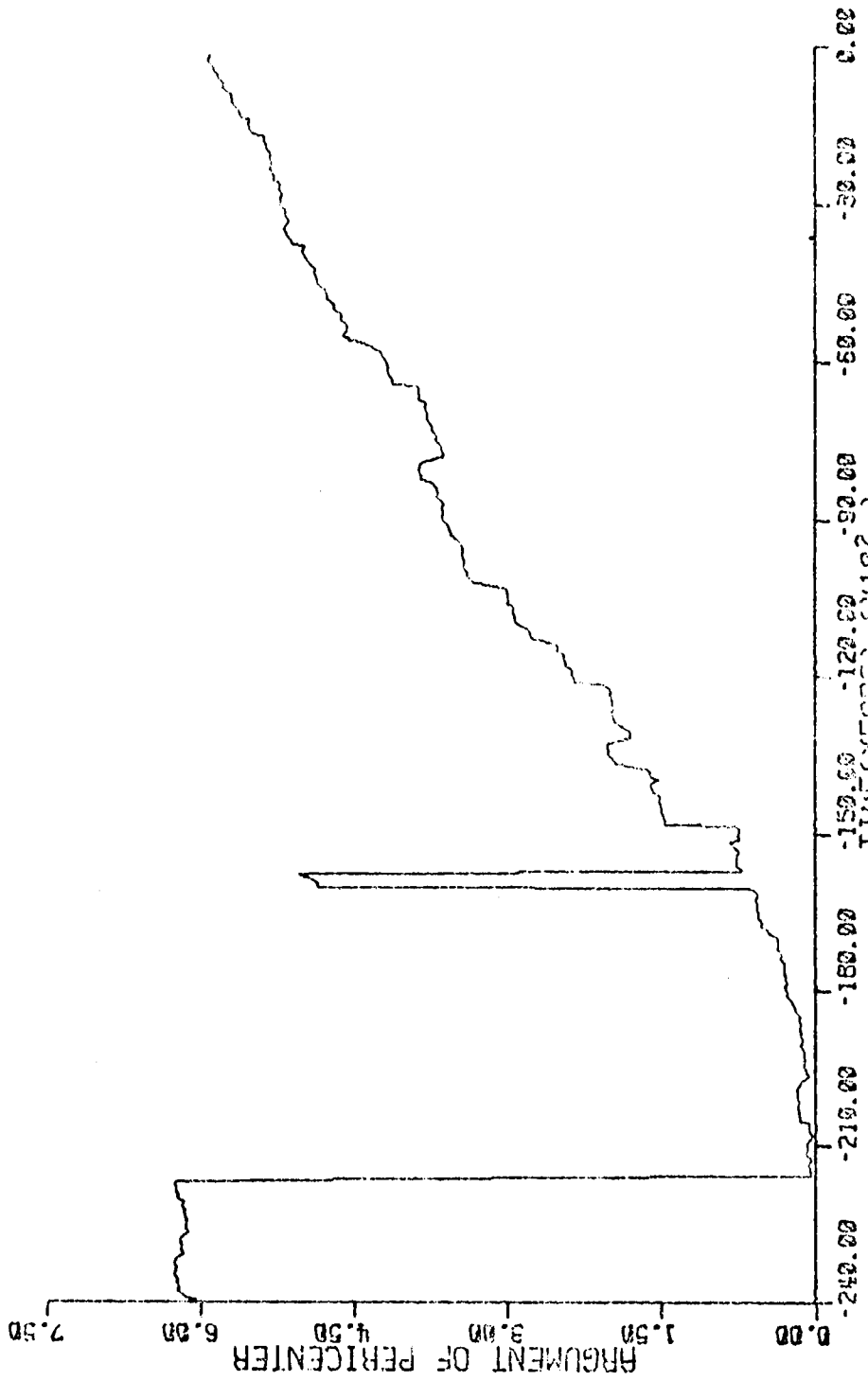

Figure 8. Variation in Chiron's Argument of Pericenter for the Last 24,000 Years.

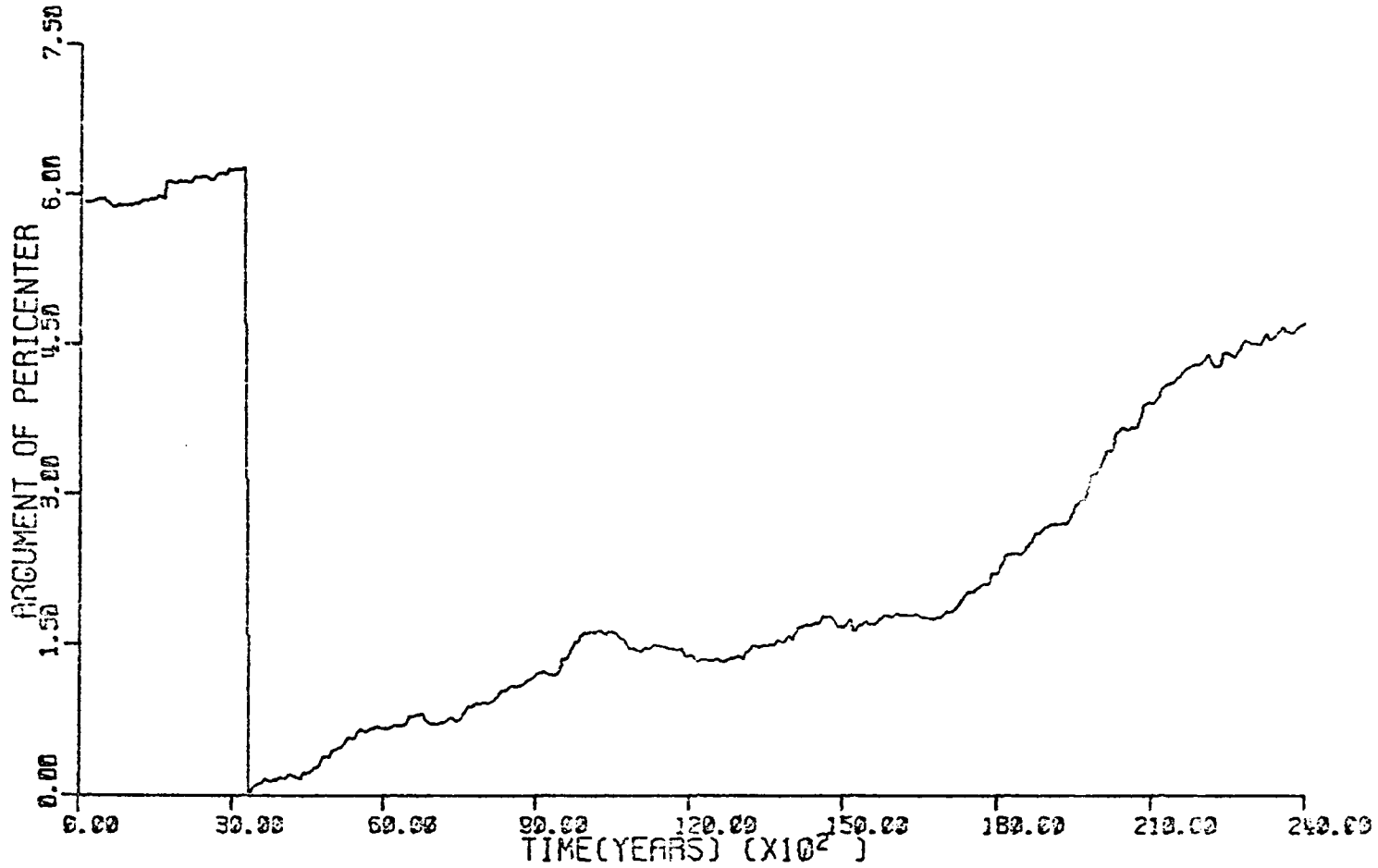

Figure 9. Variation in Chiron's Argument of Pericenter for the Next 24,000 Years.

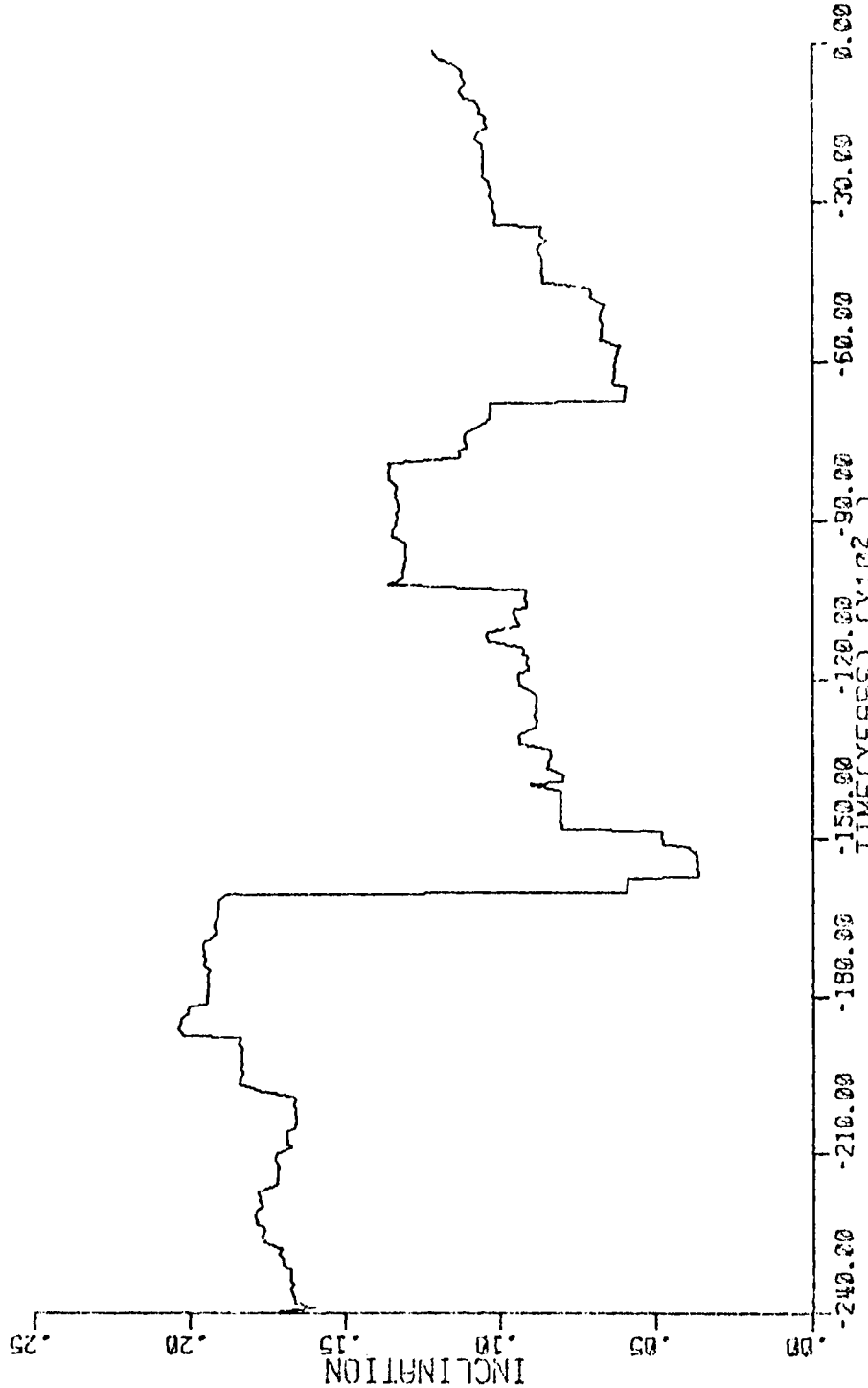

Figure 10. Variation in Chiron's Inclination for the Last 24,000 Years.

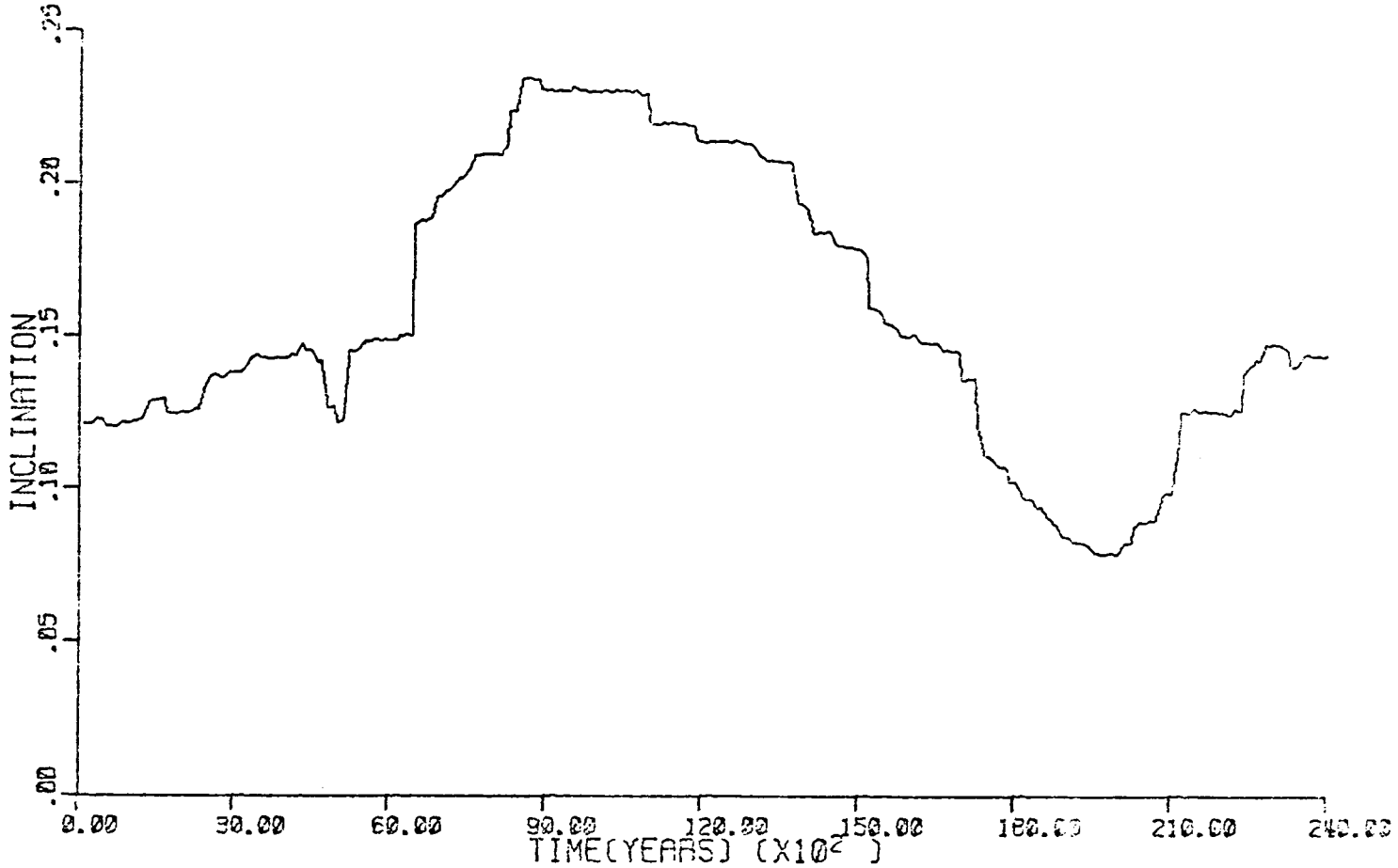

Figure 11. Variation in Chiron's Inclination for the Next 24,000 Years.

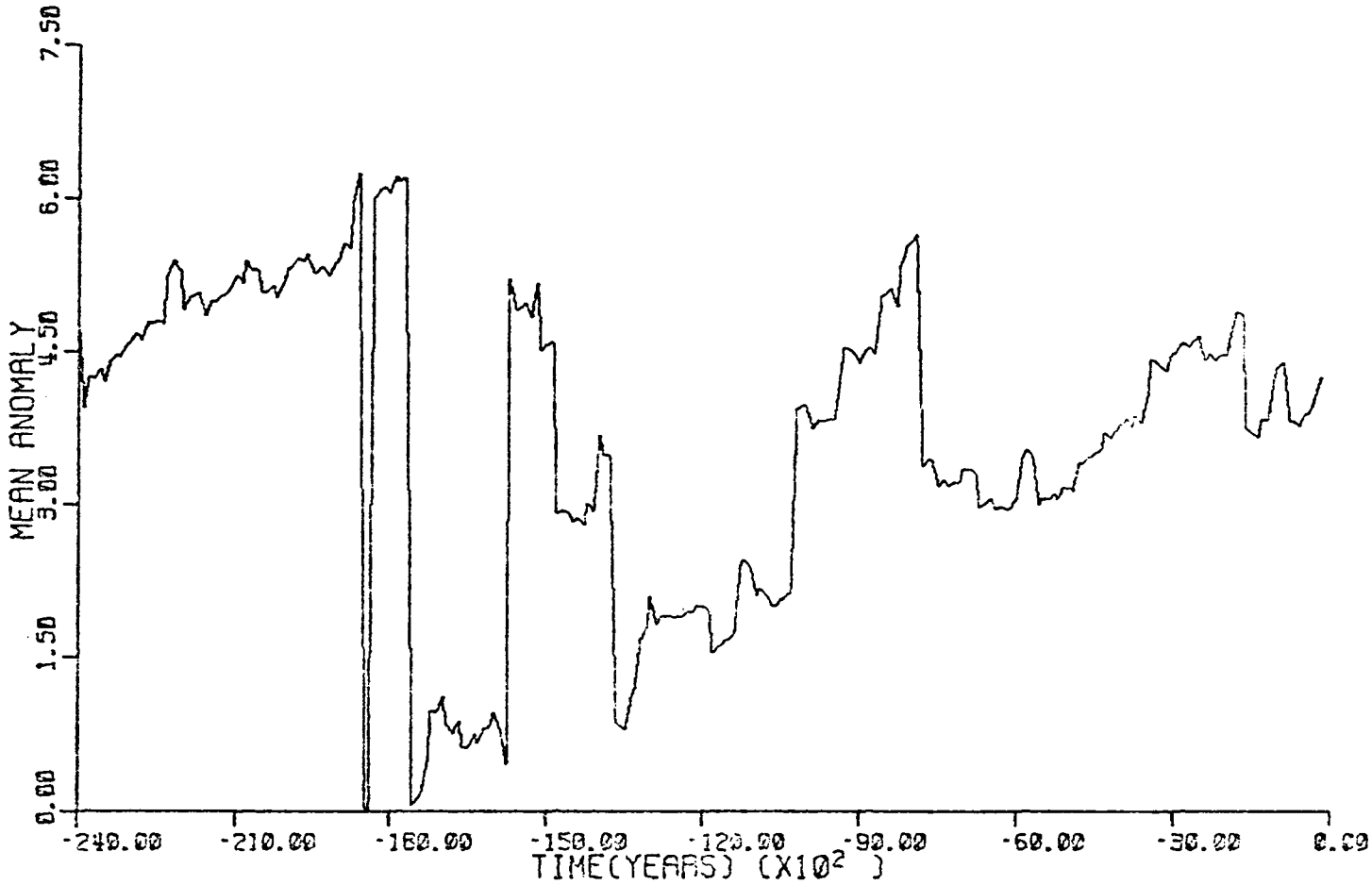

Figure 12. Variation in Chiron's Mean Anomaly for the Last 24,000 Years.

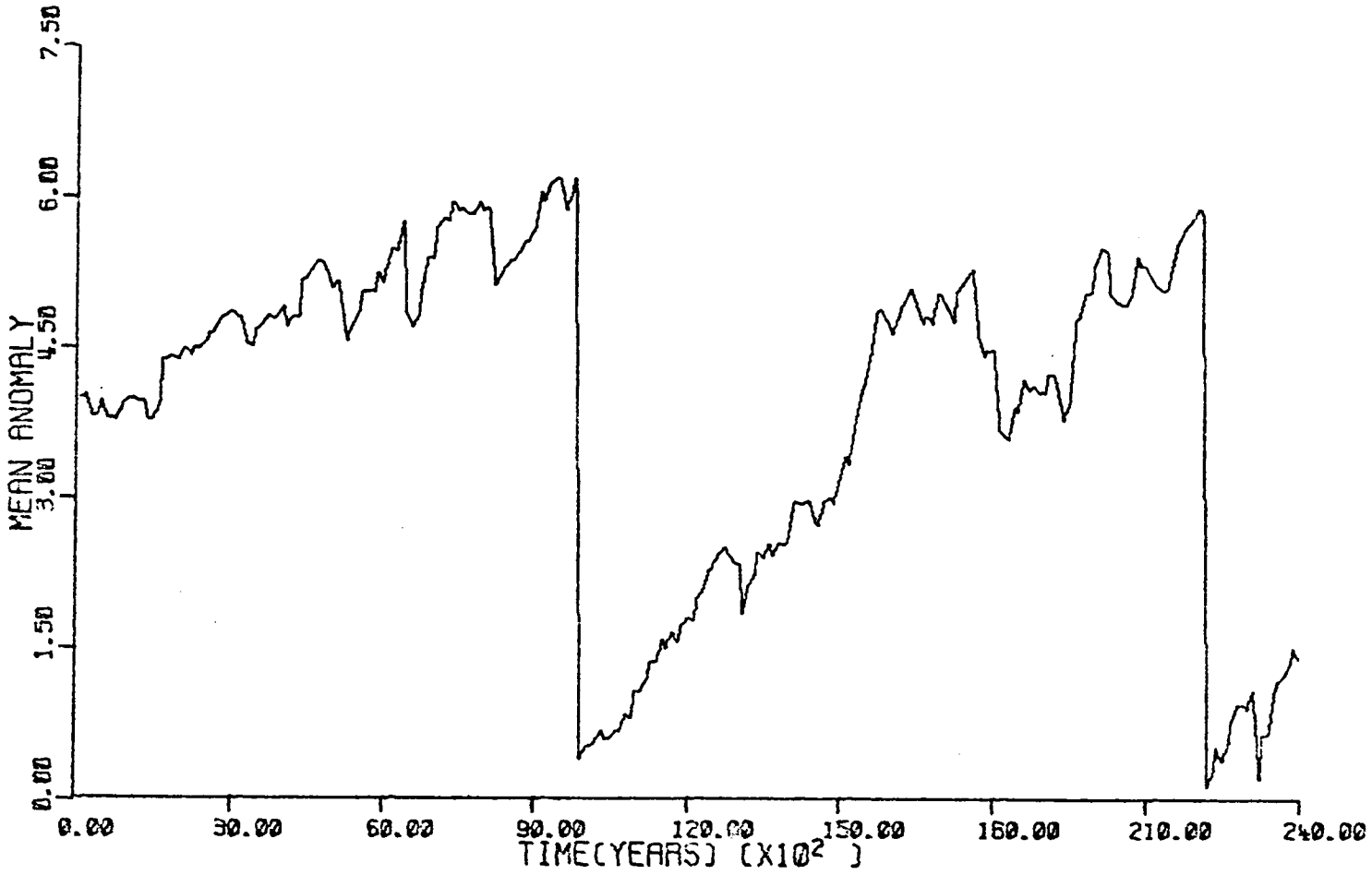

Figure 13. Variation in Chiron's Mean Anomaly for the Next 24,000 Years.

TABLE 2

PAST CLOSE APPROACHES TO SATURN BY CHIRON

Year	Distance (a.u.)
297 A.D.	0.63
1451 B.C.	0.66
2548 B.C.	0.72
4445 B.C.	0.88
4808 B.C.	0.28
5905 B.C.	0.23
6261 B.C.	0.81
7357 B.C.	0.75
8305 B.C.	0.21
8721 B.C.	0.89
9038 B.C.	0.99
9402 B.C.	0.47
10142 B.C.	0.63
10202 B.C.	0.54
10935 B.C.	0.54
11232 B.C.	0.19
11795 B.C.	0.24
11951 B.C.	0.53
12091 B.C.	0.57
12890 B.C.	0.28
13197 B.C.	0.69
13749 B.C.	0.19
14031 B.C.	0.03
16816 B.C.	0.55
17763 B.C.	0.73
17912 B.C.	0.68
19005 B.C.	0.87
20755 B.C.	0.87
21197 B.C.	0.81
21995 B.C.	0.79

time with a tolerance of 10^{-12} agrees with the former calculations for 8,000 years. Integrations with the two tolerances do not agree beyond that point. It appears that one of the biggest reasons for this disagreement is the close approach to Saturn that Chiron made in 5905 B. C. (see Table 2). Close approaches such as this one make it difficult to calculate an orbit by numerical integration. Note the large changes in the eccentricity (Figure 2) and semimajor axis (Figure 4) which resulted from this close approach.

Other close approaches (to within one a.u.) to Saturn by Chiron can be found in Table 2. These are the results of calculating Chiron's orbit for the last 24,000 years. The effects of these close approaches can be seen in the graphs of Chiron's orbital elements for the same time interval (Figures 2, 4, 6, 8, 10, and 12). According to these calculations, the closest approach Chiron has made to Saturn in the last 24,000 years occurred in 14,031 B. C. when Chiron came to almost 0.03 a.u. from Saturn. This encounter produced the smallest orbit Chiron has had in the last 24,000 years. Its perihelion after that approach was 7.4 a.u., and its aphelion was 12.4 a.u. According to the same calculations, the largest orbit that Chiron has had featured a perihelion of 9.3 a.u. and aphelion of 25.8 a.u. This was in 11,522 B.C. Only once has Chiron passed within two a.u. of Saturn and Uranus in the same

orbit. In 5905 B.C. Chiron passed by Saturn at a distance of 0.23 a.u. Twenty-four years later, Chiron passed by Uranus at a distance of 1.6 a.u. Chiron has not passed closer to Uranus than 1.2 a.u. In the past 1,000 years, Chiron has passed Saturn at a distance of 1.2 a.u. three times: in 1746, 1593, and 1098.

Chiron's orbit has also been calculated for the next 24,000 years. A comparison of the graphs of Chiron's future orbital elements (Figures 3, 5, 7, 9, 11, and 13) with the graphs of the past orbital elements (Figures 2, 4, 6, 8, 10, and 12) suggests that Chiron's past is much more interesting than its future. Chiron has apparently settled into a fairly stable orbit with no significant variations in orbital elements in the foreseeable future.

At this time information on Chiron's orbit is still rather limited. For this reason it was decided to determine what effect errors in the initial orbital elements might have on orbital elements calculated for some time in the past. One of Chiron's initial orbital elements was increased by .00001, and the orbit was re-calculated. This process was repeated five times, once for each of the remaining orbital elements. Each time, the orbital elements of the base case (no elements changed) were subtracted from the elements of the perturbed case (one element changed). The times chosen for comparison were 2,000, 4,000, 6,000, and 8,000 years in

the past. The results were put into six-by-six matrices which are shown in Tables 3 through 6. Each column of each matrix is the difference in orbital elements from the base case caused by changing one of the initial orbital elements. In Table 6, for example, if the initial eccentricity is increased by .00001, the semimajor axis will be 1.623 a.u. greater, after integrating backward 8,000 years, than it would be if no initial conditions were changed. In these tables angular measurements are in degrees. In Table 3, the differences shown are not very large, but they do suggest that 2,000 years might be the present limit for accurate calculations of Chiron's past orbital elements. Tables 4 and 5 show significant increases in these differences, and, in Table 6, some of the differences are enormous. These tables do not discredit the finding that Chiron has repeatedly passed within one a.u. of Saturn. Indeed, some of the perturbed cases show more close approaches than the base case. However, the timing of these encounters remains uncertain until a more accurate set of orbital elements is available.

TABLE 3

VARIATIONS IN CHIRON'S ORBITAL ELEMENTS AFTER 2,000 YEARS DUE TO CHANGES IN INITIAL ORBITAL ELEMENTS

Resulting Changes in Elements	Initial Elements Changed					
	e	a	M_o	ω	Ω	i
e	-.0025	-.0095	-.0013	-.0007	-.0007	.0003
a	-.0597	-.196	-.032	-.019	-.019	.005
M_o	$2^o.98$	$7^o.85$	$1^o.60$	$0^o.97$	$0^o.95$	$-0^o.25$
ω	$-0^o.17$	$-4^o.53$	$-0^o.06$	$-0^o.02$	$-0^o.02$	$0^o.006$
Ω	$0^o.0004$	$2^o.56$	$-0^o.02$	$-0^o.01$	$-0^o.01$	$0^o.002$
i	$0^o.02$	$0^o.17$	$0^o.009$	$0^o.006$	$0^o.006$	$0^o.0006$

TABLE 4

VARIATIONS IN CHIRON'S ORBITAL ELEMENTS AFTER 4,000 YEARS DUE TO CHANGES IN INITIAL ORBITAL ELEMENTS

Resulting Changes in Elements	Initial Elements Changed					
	e	a	M_o	ω	Ω	i
e	-.0602	-.0262	-.0201	-.0098	-.0094	.0018
a	-1.958	-.691	-.798	-.254	-.229	.034
M_o	$56^o.48$	$8^o.59$	$22^o.29$	$17^o.53$	$15^o.91$	$-8^o.59$
ω	$-7^o.82$	$-0^o.88$	$-2^o.11$	$-0^o.68$	$-0^o.10$	$-2^o.05$
Ω	$-1^o.41$	$-6^o.53$	$3^o.32$	$0^o.44$	$0^o.10$	$3^o.01$
i	$0^o.85$	$0^o.58$	$-2^o.60$	$-1^o.22$	$-1^o.15$	$0^o.26$

TABLE 5

VARIATIONS IN CHIRON'S ORBITAL ELEMENTS AFTER 6,000 YEARS DUE TO CHANGES IN INITIAL ORBITAL ELEMENTS

Resulting Changes in Elements	Initial Elements Changed					
	e	a	M_o	ω	Ω	i
e	-.0706	-.0311	-.0392	-.0191	-.0453	-.0204
a	-2.256	-.615	-1.214	-.39	-1.48	-.588
M_o	60°.23	-7°.90	39°.08	-22°.22	38°.03	-11°.52
ω	7°.57	11°.22	-19°.62	-22°.16	-30°.20	4°.76
Ω	-15°.10	-17°.68	12°.81	27°.14	38°.47	-2°.52
i	0°.30	1°.22	0°.47	0°.61	-1°.15	1°.21

TABLE 6

VARIATIONS IN CHIRON'S ORBITAL ELEMENTS AFTER 8,000 YEARS DUE TO CHANGES IN INITIAL ORBITAL ELEMENTS

Resulting Changes in Elements	Initial Elements Changed					
	e	a	M_o	ω	Ω	i
e	.0715	.0429	.0491	.0617	.1517	.0945
a	1.623	1.329	1.080	1.484	3.166	2.141
M_o	191°.25	-122°.84	246°.19	-136°.02	-127°.62	158°.48
ω	-10°.14	9°.63	-25°.04	-25°.84	-60°.9	-21°.42
Ω	-17°.09	36°.54	2°.64	9°.61	27°.42	-4°.96
i	-1°.94	-2°.37	-3°.19	-2°.95	-3°.74	-3°.33

CHAPTER III

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

While Chiron's orbit is fairly stable now, it has not always been that way. It is evident that Chiron's orbit has gone through significant changes in the past. This can lead to considerable speculation concerning Chiron's origin. It could be a comet, or an asteroid, or a former moon of Saturn. However, one can only speculate. The present uncertainties in Chiron's orbital elements and numerical difficulties associated with the close approaches to Saturn make calculations of Chiron's orbit very difficult for any extensive time interval. What is needed most is a better set of orbital elements, and more observations are needed to obtain a better set of orbital elements. It is hoped that a survey of past observations will uncover more observations of Chiron. It is suggested that research concentrate on observations of the sky in the area around Saturn at those times when Chiron was close to Saturn (1746, for example).

If better orbital elements are available, there may be ways to increase the accuracy of the orbit calculations. To decrease numerical difficulties with the close approaches, it may help to integrate each close approach as a hyperbolic orbit with respect to the planet

being passed. In this case, the sun would be the perturbing body. It may also help to vary the orbital elements of the major planets, instead of assuming they are constant. This can be done by integrating to find the perturbations in each planet's orbit due to the other planets and then determining a new orbit from those perturbations. In other words, the orbital elements for each planet could be recalculated periodically in the same manner as Chiron's orbital elements were recalculated in this study. With these improvements and a better set of orbital elements, a future study may well find that Chiron's past has been most interesting.

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VITA

Anthony Thomas Lyons was born in Savannah, Georgia on July 21, 1955. He grew up in Bremen, Georgia and graduated from Bremen High School in 1973. In 1977 he received a Bachelor of Science degree in Physics from West Georgia College. In September 1977 he accepted a research assistantship at The University of Tennessee Space Institute and began study toward a Master's degree. This degree was awarded in December 1978.

The author is a member of the American Institute of Aeronautics and Astronautics. Mr. Lyons will be employed with Computer Sciences Corporation after graduation.

He is married to the former Susan Wallace of Carrollton, Georgia.