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Research Note

On the possibility of a major impact on Uranus in the past century

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Abstract. It has been suggested recently by Brunini (1992b) that the systematic residuals in the computed orbit of Uranus may be explained by the influence of a major impact 100 years ago, rather than by the perturbing effects of a tenth planet. According to Brunini, this impact would be energetic enough to alter the orbit of Uranus, yet weak enough to have not caused a change in the planet's surface appearance. We demonstrate, however, that Brunini under-estimated the energetics of such an encounter by twelve orders of magnitude, and we discuss possible atmospheric and observational consequences.

Key words: planets and satellites: Uranus – interplanetary medium – celestial mechanics – stellar dynamics

1. Introduction

It has been known for some time that the orbit of Uranus deviates from that which is expected from Newtonian dynamics. To explain its motion, the gravitational perturbing effect of an undiscovered tenth planet is commonly postulated (e.g. Gomes 1989; Harrington 1988; Brunini 1992a), even though attempts to discover such a planet thus far have failed (reviewed in Croswell 1988; see also Hogg et al. 1991). While the gravitational force of a tenth planet is certainly the simplest explanation, one cannot ignore more speculative causes, (such as major impacts with large asteroids, comets, or planetesimals), without a detailed discussion of the energetics and the observational consequences.

Collisions have been invoked to explain the unusual 98° tilt of Uranus' rotation axis (Korycansky et al. 1990), and to explain the chemical composition of its atmosphere (Ip & Fernandez 1988). In what follows, however, we restrict our attention to a recent suggestion by Brunini (1992b), that the systematic residuals in Uranus' orbit can be explained if Uranus was struck by a large ($\sim 10^{-10} M_\odot$) object about 100 years ago.

We find that Brunini *underestimated* the energetics of the required collision by twelve orders of magnitude. We suggest that such a deposit of energy into Uranus, 100 years ago, would not have gone unnoticed by the experienced observers of the day. We conclude that a major impact on Uranus of the type suggested by Brunini is extremely unlikely. In Sect. 2 we reassess the energetics discussed by Brunini. In Sect. 3 we discuss the possible observational consequences. In Sect. 4 we review some historical observations that lead us to conclude that if such an impact had occurred then it would not have gone unnoticed, and in Sect. 5 we explore possible variations to the energetics of a major impact.

2. Energetics of a major impact

Following Brunini (1992b) let us consider the collision between Uranus and a $10^{-10} M_\odot$ object. As suggested by Stern (1991), objects of this class (~ 500 km diameter; density ~ 2.1 g cm^{-3}) may not be rare in the outer solar system (20–50 AU). To explain the residuals in the orbit of Uranus, Brunini's models require that Uranus receive an impulsive retardation of $8.1\ 10^{-1}$ cm s^{-1} in its tangential velocity. If we assume, for simplicity, an inelastic impact in the orbital path (i.e. a head-on collision) then conservation of momentum requires:

$$M_u v_{t_0} + m_i v_{i_0} = (M_u + m_i) v_t, \tag{1}$$

where v_{t_0} is the tangential orbital velocity of Uranus before impact, v_t is the post-impact (present day) tangential velocity, v_{i_0} is the initial velocity of the impactor, and M_u and m_i are the masses of Uranus and of the impactor. Solving for v_{i_0} gives

$$v_{i_0} = (M_u/m_i)\Delta v_t + v_t, \tag{2}$$

where $\Delta v_t \equiv v_t - v_{t_0} = -8.1\ 10^{-1}$ cm s^{-1}. The initial relative

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velocity becomes

$$v_{\mathrm{r}}=(M_{\mathrm{u}}/m_{\mathrm{i}}+1)\Delta v_{\mathrm{t}}=-3.52\,10^5\ \mathrm{cm\,s^{-1}}, \quad (3)$$

which would be the velocity at impact if Uranus and the body did not interact gravitationally (Brunini's assumed scenario). The change in the total kinetic energy of the system is therefore

$$\Delta K=\frac{M_{\mathrm{u}}v_{\mathrm{to}}^2}{2}+\frac{m_{\mathrm{i}}v_{\mathrm{io}}^2}{2}-\frac{(M_{\mathrm{u}}+m_{\mathrm{i}})v_{\mathrm{t}}^2}{2}$$

$$=\frac{M_{\mathrm{u}}(\Delta v_{\mathrm{t}})^2}{2}\left(\frac{M_{\mathrm{u}}}{m_{\mathrm{i}}}+1\right)=1.23\,10^{34}\ \mathrm{erg}, \quad (4)$$

where we used $M_{\mathrm{u}}=8.7\,10^{28}$ g and $v_{\mathrm{t}}=6.81\,10^5$ cm s^{-1} as obtained from Lang (1992) and $m_{\mathrm{i}}=2\,10^{23}$ g. We must now consider the additional energy gained as the impactor falls through the gravitational potential of Uranus. In the center of mass of the encounter, Uranus and the object fall toward each other. After the collision, this aspect of the encounter induces no net change to the orbital velocity of Uranus, yet, as we will see, this contribution dominates the kinetic energy computed from the momentum laws.

Let us calculate the kinetic energy acquired by the impacting body as it falls onto Uranus. We approximate free fall when the object comes within d, the distance from Uranus where the gravitational force of the planet equals that of the Sun

$$\frac{GM_{\mathrm{u}}}{d^2}=\frac{GM_{\odot}}{a_{\mathrm{u}}^2}, \quad (5)$$

where a_{u} is the semi-major axis of Uranus. Solving for d in terms of R_{u}, the radius of Uranus, gives

$$d=a_{\mathrm{u}}(M_{\mathrm{u}}/M_{\odot})^{1/2}=1.9\,10^{12}\ \mathrm{cm}\approx 750R_{\mathrm{u}}, \quad (6)$$

where the numerical values for a_{u}, M_{u}, R_{u}, and $M_{\odot}$, are obtained from the compilation by Lang (1992). It is important to note that as the impactor falls from d to R_{u} it will achieve $(1-R_{\mathrm{u}}/d)^{1/2}$ of the velocity it would have acquired had it fallen toward Uranus from infinity. For Uranus, this factor yields 99.9% of the escape velocity. From the difference in potential we readily compute

$$\Delta W=m_i\Delta\Phi=\frac{Gm_{\mathrm{i}}M_{\mathrm{u}}}{R_{\mathrm{u}}}\left(1-\frac{R_{\mathrm{u}}}{d}\right)\approx 4.6\,10^{35}\ \mathrm{erg} \quad (7)$$

which is nearly a factor of 40 greater than the contribution due to the kinetic energy. The total energy transferred to Uranus is therefore

$$U_{\mathrm{impact}}=\Delta W+\Delta K\approx 4.7\,10^{35}\ \mathrm{erg}, \quad (8)$$

which, we note, is *12 orders of magnitude greater* than that obtained by Brunini (1992b), and is equivalent to the total energy output generated by the Sun in 100 s.

3. Possible observational consequences

We now address the possibility that such a rapid deposition of energy will cause observable effects on the planet. If, indeed, storms are spawned by instabilities in the upper atmosphere then it is reasonable to consider the possibility that the atmosphere will be forced to react to such an impulse of energy. The detailed numerical impact models of Korycansky et al. (1990) showed that the atmospheric envelope will absorb approximately 15% of the total impact energy over $2\,10^5$ s (about two days), while the rest is deposited to the planet's core. We cannot be sure that a $10^{-10}M_{\odot}$ object will impact the solid core of the planet: If it does not, then all energy is transferred to the envelope and our argument is strengthened.

Some insight to the energetics may be gained when we consider that the increase in energy of Uranus' atmosphere is the equivalent of

$$t=\frac{0.15\,U_{\mathrm{impact}}4\pi a_{\mathrm{u}}^2}{0.75\,L_{\odot}\pi R_{\mathrm{u}}^2}\approx 3.8\,10^4\ \mathrm{yr} \quad (9)$$

of incident solar radiation, where the factor 0.75 is the fraction of solar radiation absorbed (corresponding to a bolometric geometric albedo of 0.25, Conrath et al. 1991b), and $L_{\odot}$ ($=4\,10^{33}$ erg s^{-1}) is the luminosity of the Sun. The total energy in the impact (U_{impact}) is also equivalent to the total solar energy received in two days if Uranus were placed at a distance of $2R_{\odot}$.

Remarkably, the expected increase in thermal luminosity is small. We do not know, in detail, the radial profiles of specific heat or temperature for Uranus. Rather than compute directly the thermal content of the planet, we can minimize our uncertainties if we appeal to the virial theorem to derive the order-of-magnitude total energy. Ignoring coefficients of order unity, the virial theorem gives

$$(U_{\mathrm{internal}})_0\approx\langle W_{\mathrm{u}}\rangle\approx\frac{GM_{\mathrm{u}}^2}{R_{\mathrm{u}}}\approx 2\,10^{40}\ \mathrm{erg} \quad (10)$$

for the internal binding energy. We can now compute the fractional change in mean temperature from

$$\frac{\Delta U_{\mathrm{internal}}}{(U_{\mathrm{internal}})_0}=\frac{\langle c_{\mathrm{v}}\rangle M_{\mathrm{u}}\Delta\langle T\rangle}{\langle c_{\mathrm{v}}\rangle M_{\mathrm{u}}\langle T\rangle_0}=\frac{\Delta\langle T\rangle}{\langle T\rangle_0}=2\,10^{-5}, \quad (11)$$

where $\langle c_{\mathrm{v}}\rangle$ is the mean value for the specific heat. The corresponding increase in bolometric luminosity would not be detected, even today, since the best estimate for the effective temperature of Uranus is 3.5% uncertain: $T_{\mathrm{eff}}=58\pm 2$ K (Lang 1992).

It may be more instructive, however, to consider the energy contained in the surface storms that are observed on other Jovian planets. In particular, the remarkable similarity in global properties between Uranus and Neptune (such as mass, radius, effective temperature, and rotation rate) may allow us to draw limited analogies between them. For example, if the cyclonic kinetic energy of Neptune's Great Dark Spot (GDS) is less than the amount of energy transferred to Uranus' atmosphere from the impact, then energetic arguments cannot forbid the formation of locally pronounced cloud features on Uranus, which might be detected by a careful observer.

We approximate the kinetic energy of Neptune's GDS by assuming the cyclone to be a homogeneous cylinder that rotates as a solid body with a depth $h \sim 30$ km (equal to one mixing length, Allison et al. 1991), and a diameter $D_{\rm GDS} \sim 8000$ km (Conrath et al. 1991a). Using an edge tangential velocity $v_{\rm edge} \sim 50\,{\rm m\,s^{-1}}$ (scaled from what is found for Jupiter's Great Red Spot; Smith & Hunt 1976) we derive

$$K_{\rm GDS} \approx \frac{1}{2} I \omega^2 = \frac{1}{4} M_{\rm GDS} v_{\rm edge}^2 = \frac{\pi}{16} \rho D_{\rm GDS}^2 h v_{\rm GDS}^2. \tag{12}$$

If we take for density the (over-estimated) value $\rho \sim 1\,{\rm g\,cm^{-3}}$ then

$$K_{\rm GDS} \approx 9.4\ 10^{30}\,{\rm erg}. \tag{13}$$

The ratio of the kinetic energy in Neptune's GDS to the energy deposited in Uranus' atmosphere by the impact is therefore

$$0.15 (U_{\rm impact})/K_{\rm GDS} = 7.5\ 10^3. \tag{14}$$

We conclude that the hypothesized impact on Uranus contains ample energy to instigate thousands of storms of the type observed on Neptune. The detailed formation mechanism, however, is likely to be revealed only through hydrodynamic simulations.

4. Likelihood that a major impact would go unnoticed

Can such a large deposit of energy remain unnoticed from Earth? We believe the answer is no. Brunini's probability function for the time of impact places the event at mid-year in 1896. There are dozens of recorded observation between 1870 and 1900 which make no special mention of new, obvious surface features that were independently verified.

Some observers mention very faint bands, or isolated clouds; others mention the absence of markings. Some reports make no mention of the planet's surface (the purpose being to measure the positions of the satellites), although we expect that if features were there to be noticed then these observers would have reported them. A selected chronology appears in Table 1.

At opposition, Uranus subtends 3.4″ from Earth, which is just large enough to detect surface features in the best of seeing. Atmospheric fluctuations may explain the occasional, yet spurious reports of surface patterns. Most of the

Table 1. A selected chronology of Uranus observations: 1870–1900

Dates	Observer(s)	Comments
1870–1872	Buffham	Light spots or bright zone. Concludes equator is not coincident with plane of satellites
1877–1883	Safarik	Mentions color, but never markings
1883	Schiaparelli	Spots and colors on disk, but too vague to sketch
May–June 1883	Young	Very faint belts repeatedly seen by several observers. Tilted 20° from plane of satellites
March–April 1884	Thollen Perrotin Lockyer	Dark spots near center of disk, white spot (sometimes a white band) most easily seen near limb. Rotation rate ~10 h. Hemispheres differ in albedo
April 1890	Holden	Two faint bands nearly E–W
April–June 1891	Holden Schaeberle	Several times sees very faint bands at various angles. Drawings included
April 1893–May 1895	Henderson	Suspects belts almost N–S
April 1894–August 1895	Barnard	Plane tilted by 20°–30° compared with satellites. No mention of surface features
April–July 1895	Brenner	Clouds in belt are somewhat inclined with respect to the orbital plane of the satellites. Rotation period 8.5 h
May 1896	Roberts	Belts at 45° to ecliptic (i.e. not in plane of satellite orbits)
June 1895 April–June 1897	Schaeberle	No mention of surface features
April–July 1898	Aitken	No mention of surface features
October 1899–January 1900	See	No mention of surface features

Note: In 1881, the line of sight to Uranus permitted an equatorial view. By 1901, the orientation of Uranus was pole-on.

"belt" observations do not coincide with the currently-accepted position of the equatorial plane of Uranus, and several of the inferred rotation rates are much faster than the modern values.

A feature must show dramatic contrast with the planet's surface to be recorded with confidence. While we cannot guarantee that high-contrast features are an inevitable consequence of a major impact, it remains true that good conditions do permit an experienced observer to notice patterns in the atmosphere of Uranus. While one should not trust the observations fully, we do believe they may be used, in general, as evidence for the lack of confirmed catastrophic features in Uranus' atmosphere over the period in question.

5. Discussion

Let us now consider the extent to which our conclusions would change if we used parameters other than those prescribed by Brunini's (1992b) models. The only observational constraint is the *inferred* retardation in the orbit velocity of Uranus. From a purely kinematic approach this can be accomplished with any combination of mass and initial velocity for the impacting body that satisfies Eq. (2).

For a given retardation, the choice of mass and initial velocity of the impactor affects the energetics of the encounter. If we normalize the mass of the impactor to $10^{-10}M_\odot$ ($x=m_i/10^{-10}M_\odot$), and if we normalize the change in the planet's velocity to the value given by Brunini ($\delta=|\Delta v|/8.1\,10^{-1}$ cm s^{-1}), then we can rewrite Eq. (8) in dimensionless form

$$U_{\rm impact}(x,\delta)/10^{35}\ {\rm erg}=4.6x+0.123(\delta^2/x). \qquad (15)$$

Equation (15) is plotted in Fig. 1 for $\delta=0.01, 0.1, 1$, and 10. Note that the function always contains a minimum: for small masses $U_{\rm impact}$ is dominated by the kinetic term, while for high masses $U_{\rm impact}$ is dominated by the gravitational energy of the body. If we minimize Eq. (15), we find that for an inelastic collision, the smallest transfer energy is obtained for $x=0.164\delta$, which gives

$$U_{\rm impact}({\rm min})=1.50\,10^{35}\delta\ {\rm erg}. \qquad (16)$$

Equation (16) expresses the remarkable result that if one invokes a major impact to account for any observed change in the orbit velocity of Uranus, then the energy transferred to the planet must be *at least* $1.50\,10^{35}\delta$ erg. If, for example, Brunini overestimated the change in Uranus' velocity by a factor of two, then the minimum impact energy drops only to $U_{\rm impact}({\rm min})\approx 0.75\,10^{35}$ erg.

We further note that if one wishes to achieve the required change in orbit velocity with a very small object, then the object's initial velocity must be greater than the local escape velocity of the solar system: $v_{\rm esc}({\rm local})=(2)^{1/2}v_t$. If the impactor in Brunini's models is gravitationally bound to the solar system, then its mass must be at least

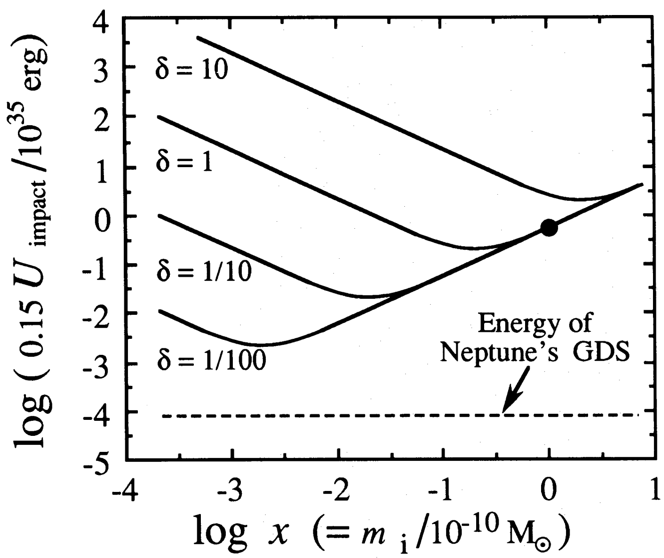

Fig. 1. Energy of a Uranus-object impact as a function of object mass obtained from Eq. (15). The curves are loci of constant impulse velocity for Uranus, normalized to Brunini's (1992b) value of $|\Delta v_t|=8.1\,10^{-1}$ cm s^{-1}. The dot represents the mass and energy appropriate for a $10^{-10}M_\odot$ object that impacts on Uranus with $\delta=1$. Note that the curves display minima: for small masses the impact energy is dominated by the initial kinetic energy of the object, while for high masses the impact energy is dominated by the gravitational energy of the body. In all cases, the energy of impact is very high relative to the estimated energy content of observable atmospheric features on Neptune, such as its Great Dark Spot

$m_i\approx 0.2\,10^{-10}M_\odot$ to impart the inferred change in Uranus velocity.

6. Summary and conclusions

We have shown from simple arguments of dynamics and energetics that an inelastic encounter between a $10^{-10}M_\odot$ object and the planet Uranus will dissipate $3.76\,10^{35}$ erg, which is 12 orders of magnitude greater than what was estimated by Brunini (1992b). For comparison, this is more than 10^4 times the total rotational kinetic energy estimated for Neptune's Great Dark Spot. The global similarities between Uranus and Neptune (e.g. mass, radius, effective temperature, and rotation rate) and the energetics of the impact suggest that one cannot exclude the triggering of similar surface features on Uranus. In an attempt to explain the systematic orbit residuals for Uranus, Brunini suggests that the impact occurred in mid-1886. Among dozens of observations made by experienced observers from 1870 to 1900, none make any mention of large changes in the brightness or surface features of Uranus. We conclude that it is very unlikely that Uranus had a major impact 100 years ago, and that one cannot appeal to catastrophic impacts as the cause of systematic residuals in

Uranus' orbit without simultaneously addressing the atmospheric effects of a non-negligible deposit of energy. We urge that hydrodynamic simulations be conducted to explore the detailed observational consequences of such a collision.

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References

Aitken R.G., 1898, AJ 19, 76
Allison M., Beebe R.F., Conrath B.J., Hinson D.P., Ingersoll A.P., 1991, in: Bergstrahl J.T., Miner E.D., Matthews M.S. (eds.) Uranus. Tucson: Univ. of Arizona Press, p. 253
Barnard E.E., 1896, AJ 16, 73
Brenner L., 1897, JBAA 7, 393
Brunini A., 1992a, A&A 255, 401
Brunini A., 1992b, A&A 264, 292
Buffham W., 1872, MNRAS 33, 164
Conrath B.J., Flasar F.M., Gierasch, 1991a, J. Geophys. Res. 96, 18931
Conrath B.J., Pearl J.C., Appleby J.F., Lindal G.F., Orton G.S., Bézard B., 1991b, in Bergstrahl J.T., Miner E.D., Matthews M.S. (eds.) Uranus. Tucson: Univ. of Arizona Press, p. 204
Croswell K., 1988, Astronomy 16, 30
Gomes R.S., 1989, Icarus 80, 334
Harrington R.S., 1988, AJ 96, 1476
Henderson R., 1897, JBAA 7, 57
Hogg D.W., Quinland D.G., Tremaine S., 1991, AJ 101, 2274
Holden E.S., 1890, PASP 2, 197
Holden E.S., Schaeberle J.M., Keeler J.E., 1891, PASP 3, 283
Ip W.-H., Fernandez J.A., 1988, Icarus 74, 47
Korycansky D.G., Bodenheimer P., Cassen P., Pollack J.B., 1990, Icarus 84, 528
Lang K.R., 1992, Astrophysical Data: Planets and Stars. Springer, New York, p. 46
Roberts C., 1896, JBAA 6, 389 & 435
Roberts C., 1897, JBAA 7, 55
Safarik A., 1883, Astr. Nachr. 105, 131
Schaeberle J.M., 1897, AJ 18, 5
Schiaparelli G.V., 1883, Astr. Nachr. 106, 81 & 125
See T.J.J., 1900, Astr. Nachr. 153, 289
Smith B.A., Hunt G.E., 1976, in: Gehrels T. (ed.) Jupiter. Tucson: Univ. of Arinoza Press, p. 564
Stern S.A., 1991, Icarus 90, 271
Thollen, Perrotin J., Lockyer J.N., 1883, Comptes Rendus 98, 12 & 16
Young C.A., 1883, Sidereal Mess. 2, 254

Note added in proof: It was called to our attention by J. Applegate that since most of the mass of Uranus is degenerate, then our assumption that the total thermal content of Uranus can be derived from the virial theorem may be over-simplified. A recent model for Uranus gives 80% of its mass as ices (Podolak & Reynolds 1987, Icarus 70, 31). If we use a specific heat of ices at high pressures of $4.1\,10^7\,\mathrm{erg\,K^{-1}\,g^{-1}}$ (Podolak & Reynolds 1981, Icarus 46, 40), then assuming one Uranus mass of ices at a mean temperature of 500 K (a conservative estimate chosen between $T_{\rm eff} \approx 60$ K and $T_{\rm core} \approx 3500$ K) gives an internal thermal energy of $U_{\rm thermal} \approx 2\,10^{39}$ erg, [compared with $2\,10^{40}$ erg obtained via the virial theorem in Eq. (10)]. This remains nearly 5000 times greater than total impact energy, $U_{\rm impact} \approx 4.6\,10^{35}$ erg, so our conclusions drawn from Eq. (11) are unaffected.