Icarus 199 (2009) 458–476

Contents lists available at ScienceDirect

Icarus

www.elsevier.com/locate/icarus

Titania's radius and an upper limit on its atmosphere from the September 8, 2001 stellar occultation

T. Widemann [a,*], B. Sicardy [a,b], R. Dusser [c], C. Martinez [d], W. Beisker [e], E. Bredner [e], D. Dunham [f], P. Maley [g], E. Lellouch [a], J.-E. Arlot [h], J. Berthier [h], F. Colas [h], W.B. Hubbard [i], R. Hill [i], J. Lecacheux [a], J.-F. Lecampion [j], S. Pau [a], M. Rapaport [j], F. Roques [a], W. Thuillot [h], C.R. Hills [k], A.J. Elliott [l], R. Miles [l], T. Platt [m], C. Cremaschini [n], P. Dubreuil [o], C. Cavadore [p], C. Demeautis [p], P. Henriquet [q], O. Labrevoir [q], G. Rau [r], J.-F. Coliac [s], J. Piraux [t], Ch. Marlot [u], C. Marlot [u], F. Gorry [u], C. Sire [u], B. Bayle [v], E. Simian [w], A.M. Blommers [x], J. Fulgence [y], C. Leyrat [z], C. Sauzeaud [z], B. Stephanus [z], T. Rafaelli [aa], C. Buil [ab], R. Delmas [ab], V. Desnoux [ab], C. Jasinski [ab], A. Klotz [ab], D. Marchais [ab], M. Rieugnié [ac], G. Bouderand [ad], J.-P. Cazard [ad], C. Lambin [ad], P.-O. Pujat [ad], F. Schwartz [ad], P. Burlot [ae], P. Langlais [ae], S. Rivaud [ae], E. Brochard [af], Ph. Dupouy [ag], M. Lavayssière [ag], O. Chaptal [ah], K. Daiffallah [ai], C. Clarasso-Llauger [aj], J. Aloy Doménech [aj], M. Gabaldá-Sánchez [aj], X. Otazu-Porter [aj], D. Fernández [ak], E. Masana [ak], A. Ardanuy [al], R. Casas [al], J.A. Ros [al], F. Casarramona [al], C. Schnabel [al], A. Roca [al], C. Labordena [al], O. Canales-Moreno [c], V. Ferrer [am], L. Rivas [am], J.L. Ortiz [ap], J. Fernández-Arozena [aq], L.L. Martín-Rodríguez [aq], A. Cidadão [ar], P. Coelho [ar], P. Figuereido [ar], R. Gonçalves [ar], C. Marciano [ar], R. Nunes [ar], P. Ré [ar], C. Saraiva [ar], F. Tonel [ar], J. Clérigo [as], C. Oliveira [as], C. Reis [as], B.M. Ewen-Smith [at], S. Ward [at], D. Ford [at], J. Gonçalves [au], J. Porto [au], J. Laurindo Sobrinho [an,av], F. Teodoro de Gois [ar], M. Joaquim [ao], J. Afonso da Silva Mendes [ao], E. van Ballegoij [x], R. Jones [aw], H. Callender [aw], W. Sutherland [aw], S. Bumgarner [f], M. Imbert [ax], B. Mitchell [ax], J. Lockhart [ax], W. Barrow [ax], D. Cornwall [ax], A. Arnal [ay], G. Eleizalde [ay], A. Valencia [ay], V. Ladino [az], T. Lizardo [az], C. Guillén [az], G. Sánchez [az], A. Peña [az], S. Radaelli [az], J. Santiago [az], K. Vieira [az], H. Mendt [ba], P. Rosenzweig [bb], O. Naranjo [bb], O. Contreras [bb], F. Díaz [bb], E. Guzmán [bb], F. Moreno [bb], L. Omar Porras [bb], E. Recalde [bd], M. Mascaró [bd], C. Birnbaum [bc], R. Cósias [bd], E. López [bd], E. Pallo [bd], R. Percz [bd], D. Pulupa [bd], X. Simbaña [bd], A. Yajamín [bd], P. Rodas [bd], H. Denzau [e], M. Kretlow [e], P. Valdés Sada [be], R. Hernández [be], A. Hernández [bf], B. Wilson [bg], E. Castro [bh], J.M. Winkel [x]

[a] *Observatoire de Paris, LESIA, 5, Place Jules Janssen, 92195 Meudon cedex, France*
[b] *Université Pierre et Marie Curie et Institut Universitaire de France, 103 boulevard Saint-Michel, F-75005 Paris, France*
[c] *European Asteroidal Occultation Network (EAON), 60 impasse des Lauriers, F-84400 Apt, France*
[d] *Instituto Superior de Ciencias Astronómicas, and Liga Iberoamericana de Astronomía, Buenos Aires, Argentina*
[e] *International Occultation Timing Association, European Section (IOTA/ES), Bartold-Knaust-Strasse 8, 30459 Hannover, Germany*
[f] *International Occultation Timing Association (IOTA), PO Box 6356, Kent, WA 98064-6356, USA*
[g] *IOTA, 4535 Cedar Ridge Trail, Houston, TX 77059, USA*
[h] *Observatoire de Paris, IMCCE, 77 Avenue Denfert-Rochereau, 75014 Paris, France*
[i] *Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA*
[j] *Observatoire de Bordeaux, 2, Rue de l'Observatoire, BP 89, 33270 Floirac, France*
[k] *Simoco Digital Systems Ltd, Radio House, St Andrews Road, Cambridge, Cambridgeshire, CB4 1GR, United Kingdom*
[l] *British Astronomical Association, Asteroids and Remote Planets Section, Lower Earley, Reading, RG6 4AZ, United Kingdom*
[m] *Starlight Xpress, Foxley Green Farm, Ascot Road, Holyport, Berkshire, SL6 3LA, United Kingdom*
[n] *Osservatorio di Trieste, Via G.B. Tiepolo 11, I-34143 Trieste, Italy*
[o] *Astrocam, F-06790 Aspremont, France*
[p] *Observatoire du Tim, Chemin La Chapelle, 04700 Puimichel, France*
[q] *Centre d'Astronomie, 04870 St.-Michel l'Observatoire, France*
[r] *Observatoire de Haute-Provence/CNRS, 04870 St.-Michel l'Observatoire, France*
[s] *Association Marseillaise d'Astronomie, 213, Avenue de Montolivet, F-13012 Marseille, France*
[t] *Laboratoire de Mécanique et d'Acoustique, UPR 7051, 31 chemin Joseph-Aiguier, F-13402 Marseille cedex 20, France*
[u] *ASCT Section Astronomie, 3 rue du 19 mars 1962, F-76400 Toussaint, France*
[v] *Home observatory, F-13300 Salon de Provence, France*
[w] *Astronomie en Crau, F-13310 Saint-Martin de Crau, France*
[x] *Dutch Occultation Association, Boerenweg 32, NL 5944 EK Arcen, The Netherlands*
[y] *Impasse de Biaune, F-21160 Corcelles les Monts, France*
[z] *Observatoire du Collège de l'Etang de l'Or, UAI 180, 34130 Mauguio, France*
[aa] *Observatoire de Malibert, F-34360 Saint-Chinian, France*
[ab] *Association des Utilisateurs de Détecteurs Electroniques (AUDE), c/o F. Colas, 45, Avenue Reille, 75014 Paris, France*
[ac] *Observatoire d'astronomie de Saint-Caprais, F-81800 Rabastens, France*
[ad] *Observatoire Jolimont, 1 Avenue Camille-Flammarion, 31500 Toulouse, France*

0019-1035/$ – see front matter
doi:10.1016/j.icarus.2008.09.011

[ae] Société d'astronomie populaire poitevine (SAPP), Centre Socio culturel du Clos Gaultier, F-86000 Poitiers, France
[af] Observatoire de Saint-Savinien sur Charente, F- 17350 Saint-Savinien sur Charente, and Association Nationale pour la Protection du Ciel Nocturne (A.N.P.C.N), c/o S.A.F, 3 rue Beethoven, F-75016 Paris, France
[ag] Observatoire de Dax, rue Pascal Lafitte, F-40100 Dax, France
[ah] Centre de Documentation Spécialisé en Astronomie – CDSA Martinique, 34 Boulevard Amilcar Cabral, Cluny – BP 411, F-97200 Fort-de-France, France
[ai] Observatory of Algiers, CRAAG, Route de l'Observatoire, BP 63, Bouzaréah 16340, Algiers, Algeria
[aj] Agrupación Astronómica de Barcelona, Carrer Aragó 141-143, 2-E, 08015 Barcelona, Spain
[ak] Departamento de d'Astronomia i Meteorologia, IEEC-Universitat de Barcelona, Avenue Diagonal 647, 08028 Barcelona, Spain
[al] Agrupación Astronómica de Sabadell, C. Prat de la Riba, s/n, Apdo 50, Sabadell, Barcelona, Spain
[am] Asociación Valenciana de Astronomía, 16 Bajo Valencia, 46014 Valencia, Spain
[an] Sociedade Portuguesa de Astronomia, Centro de Astrofísica da Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
[ao] Associação de Astrónomos Amadores da Madeira (AAAM), Villas da Bela Vista, Moradia X, 9125-103 Caniço, Madeira, Portugal
[ap] Instituto de Astrofísica de Andalucía, Apdo. 3004, 18080 Granada, Spain
[aq] Agrupación Astronómica Isla de La Palma (AAP), Apartado de Correos 449, 38700 Santa Cruz de La Palma, Provincia de Santa Cruz de Tenerife, Islas Canarias, Spain
[ar] Associação Portuguesa de Astrónomos Amadores (APAA), Rua Alexandre Herculano 57-4° Dto, 1250-010 Lisboa, Portugal
[as] Associação Nacional de Observação Astrónomica (ANOA), Apartado 582, 2430 Marinha Grande, Portugal
[at] Centro de Observação Astronómica no Algarve (COAA), Poio, 8500 Portimão, Portugal
[au] Núcleo Açoriano da Associação Portuguesa de Astrónomos Amadores (NAAPAA), Açores, Portugal
[av] Universidade da Madeira, Departamento de Matemática e Engenharias, Grupo de Astronomia, Campus da Penteada, 9000-390 Funchal, Madeira, Portugal
[aw] Barbados Astronomical Society, Harry Bayley Observatory, Bridgetown, St. Michael, Barbados
[ax] Trinidad & Tobago Astronomical Society, Sir Frank Stockdale Building, The University of the West Indies (UWI), St-Augustine Campus, Trinidad and Tobago
[ay] Observatorio Arval, Santa Teresa, Caracas, Venezuela
[az] Asociación Larense de Astronomıa (ALDA), Barquisimeto, Lara, Venezuela
[ba] American Association of Variable Star Observers, 49 BayState Rd., Cambridge, MA 02138, USA
[bb] Universidad de Los Andes, Facultad de Ciencias, 5101, Mérida, Venezuela
[bc] Cité des Sciences et de l'Industrie, 30 avenue Corentin-Cariou, 75930 Paris cedex 19, France
[bd] Observatorio Astronómico de Quito, Parque de la Alameda, PO Box 17-01-165, Quito, Ecuador
[be] Universidad de Monterrey, Departamento de Física y Matemáticas, Avenue I. Morones Prieto, 4500 Pte., San Pedro Garza García, N.L. 66238, Mexico
[bf] Asociación Panamena de Aficionados de la Astronomia, Panama
[bg] George Observatory, Brazos Bend State Park, Houston, TX 77030, USA
[bh] Universidad Autónoma de Nuevo Leon, Facultad de Ciencias Físico Matemáticas, Avenue Universidad s/n, Ciudad Universitaria, San Nicolás de los Garza, N.L. 66451, Mexico

ARTICLE INFO

Article history:
Received 14 April 2008
Revised 1 August 2008
Accepted 22 September 2008
Available online 25 October 2008

Keywords:
Occultations
Uranus, satellites
Satellites, shapes
Satellites, dynamics
Ices
Satellites, atmospheres

ABSTRACT

On September 8, 2001 around 2 h UT, the largest uranian moon, Titania, occulted Hipparcos star 106829 (alias SAO 164538, a V = 7.2, K0 III star). This was the first-ever observed occultation by this satellite, a rare event as Titania subtends only 0.11 arcsec on the sky. The star's unusual brightness allowed many observers, both amateurs or professionals, to monitor this unique event, providing fifty-seven occultations chords over three continents, all reported here. Selecting the best 27 occultation chords, and assuming a circular limb, we derive Titania's radius: $R_T = 788.4 \pm 0.6$ km (1-σ error bar). This implies a density of $\rho = 1.711 \pm 0.005$ g cm^{-3} using the value $GM = (2.343 \pm 0.006) \times 10^{11}$ m^3 s^{-2} derived by Taylor [Taylor, D.B., 1998. Astron. Astrophys. 330, 362–374]. We do not detect any significant difference between equatorial and polar radii, in the limit $r_{eq} - r_{po} = -1.3 \pm 2.1$ km, in agreement with *Voyager* limb image retrieval during the 1986 flyby. Titania's offset with respect to the DE405 + URA027 (based on GUST86 theory) ephemeris is derived: $\Delta\alpha_T \cos(\delta_T) = -108 \pm 13$ mas and $\Delta\delta_T = -62 \pm 7$ mas (ICRF J2000.0 system). Most of this offset is attributable to a Uranus' barycentric offset with respect to DE405, that we estimate to be: $\Delta\alpha_U \cos(\delta_U) = -100 \pm 25$ mas and $\Delta\delta_U = -85 \pm 25$ mas at the moment of occultation. This offset is confirmed by another Titania stellar occultation observed on August 1st, 2003, which provides an offset of $\Delta\alpha_T \cos(\delta_T) = -127 \pm 20$ mas and $\Delta\delta_T = -97 \pm 13$ mas for the satellite. The combined ingress and egress data do not show any significant hint for atmospheric refraction, allowing us to set surface pressure limits at the level of 10–20 nbar. More specifically, we find an upper limit of 13 nbar (1-σ level) at 70 K and 17 nbar at 80 K, for a putative isothermal CO_2 atmosphere. We also provide an upper limit of 8 nbar for a possible CH_4 atmosphere, and 22 nbar for pure N_2, again at the 1-σ level. We finally constrain the stellar size using the time-resolved star disappearance and reappearance at ingress and egress. We find an angular diameter of 0.54 ± 0.03 mas (corresponding to 7.5 ± 0.4 km projected at Titania). With a distance of 170 ± 25 parsecs, this corresponds to a radius of 9.8 ± 0.2 solar radii for HIP 106829, typical of a K0 III giant.

1. Introduction

Among the various techniques used to probe the physical properties of distant objects in the Solar System, ground-based stellar occultations are especially powerful. They provide kilometric accuracies or better on sizes and shapes, and may reveal tenuous atmospheres down to a few tens of nbar, as stellar rays are differentially refracted by a possible rarefied gas near the surface. On September 8, 2001 the bright (V = 7.2) Hipparcos-catalog star HIP 106829—a K0 III giant—was occulted by Titania, the largest uranian satellite (Table 1), which angular diameter subtends 0.11 arcsec only on the sky. This rare event was independently predicted by Jean Meeus (Belgium) in 1999 and later by one of us (Claudio Martinez, Argentina) in 2001.

A great variety of observations were made using both small portable telescopes and larger, fixed instruments. The brightness of HIP 106829 allowed an exceptionally high number of observers to gather timings for the event, and light curves for some of them, using a wide variety of acquisition systems and timing tech-

* Corresponding author.
E-mail address: thomas.widemann@obspm.fr (T. Widemann).