THE ASTRONOMICAL JOURNAL, 121:2800–2803, 2001 May

MULTICOLOR PHOTOMETRY OF THE URANUS IRREGULAR SATELLITES SYCORAX AND CALIBAN[1]

MICHELE MARIS
Osservatorio Astronomico di Trieste, via G. B. Tiepolo 11, I-34131 Trieste, Italy; maris@ts.astro.it
GIOVANNI CARRARO
Dipartimento di Astronomia, Universitá di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy;carraro@pd.astro.it
GABRIELE CREMONESE
Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy; cremonese@pd.astro.it
AND
MARCO FULLE
Osservatorio Astronomico di Trieste, via G. B. Tiepolo 11, I-34131 Trieste, Italy; fulle@ts.astro.it

Received 2000 October 11; accepted 2001 January 22

ABSTRACT

We report on accurate *BVRI* photometry for the two Uranian irregular satellites Sycorax and Caliban. We derive colors showing that Sycorax is bluer than Caliban. Our data allow us to detect a significant variability in Caliban's light curve, which suggests an estimated period of about 3 hr. Although it is the brighter of the two bodies, Sycorax does not display a strong, statistically significant variability. However, our data seem to suggest a period of about 4 hr.

Key words: planets and satellites: general — planets and satellites: individual (Caliban, Sycorax)

1. INTRODUCTION

A couple of new Uranian satellites, named Sycorax (S/1997 U1) and Caliban (S/1997 U2), with an orbital semimajor axis of 253 and 305 Uranian radii, respectively, were discovered in 1997 by Gladman et al. (1998). This solved the peculiarity at that time that Uranus appeared to be the only giant planet in the solar system without irregular satellites, despite accurate searches carried out in the past (Christie 1930; Kuiper 1961; Smith 1984; Cruikshank & Brown 1986).

Giant gaseous planets are characterized by a complex system of dust rings and satellites. From the point of view of orbital dynamics, the satellites of the giant gaseous planets belong to two classes: regular and irregular. The former are characterized by orbits with a small eccentricity that are very close to the planet's equatorial plane and always show a prograde motion. The latter follow orbits that may have a large ellipticity, semimajor axis, and inclination. Moreover, they may exhibit both prograde and retrograde motions. According to Pollack, Burns, & Tauber (1979) the two classes of satellites suggest quite a different evolution. Regular satellites are supposed to be born in the same subnebula from which the planet originated. On the other hand, irregular satellites might be planetesimals captured inside the planet subnebula by gas drag just before the subnebula collapsed. Eventually the captured planetesimals were fragmented by dynamical pressure due to the gas drag and were dispersed by collisions with other objects already present in the subnebula (Pollack et al. 1979). Following this scheme, it is evident that the study of irregular satellites is important in the context of the solar system origin. In particular, it could be interesting to compare the newly discovered Uranian irregular satellites with other classes of minor bodies in the outer solar system, i.e., Kuiper belt and Centaurus objects.

The faintness of the new satellites (Gladman et al. 1998 report $R_{\rm Syc} \approx 20.4$ and $R_{\rm Cal} \approx 21.9$ mag) made it difficult to determine their photometric properties. Colors are reported by Gladman et al. (1998) with 0.1 mag accuracy, suggesting that Sycorax and Caliban are reddened with respect to the Sun, in contrast with Uranus and its regular satellites. Moreover, the low photometric accuracy ($\sim$0.1 mag) prevented them from obtaining a light curve and hence an estimate of the rotation period for both satellites.

To improve the present knowledge, Sycorax and Caliban have been observed with the ESO New Technology Telescope (NTT). We obtained magnitudes in the *B*, *V*, *R*, and *I* bands with accuracy of 0.03 mag, and we obtain color and light curves.

The paper is organized as follows: § 2 describes the data acquisition and reduction; § 3, the colors; and § 4, the light curve. Final remarks and conclusions are given in § 5.

2. DATA ACQUISITION AND REDUCTION

Observations were conducted at La Silla on 1999 October 8 and 9, using the Tektronix 2024 × 2024 pixel CCD 36 mounted in the red EMMI arm of the 3.6 m ESO NTT. The first night was photometric, with an average seeing of 1".0, whereas the second one was not photometric. The scale on the chip is 0".27 pixel^{-1}, and the array covers about 9 × 9 arcmin^2 in the sky. Details of the observing run for the two satellites are given in Tables 1 and 2. Preprocessing, which includes bias and flat-field corrections, has been done by using standard routines in the ESO MIDAS package.

Instrumental magnitudes have been extracted at Padua University, using the DAOPHOT and accompanying ALLSTAR package (Stetson 1991) in the MIDAS environment. The errors in Tables 1 and 2 are assumed to be normally distributed and are 1 σ.

---

[1] Based on observations carried out at ESO La Silla (Chile). See the Asteroid Properties Database (1993), http://pdssbn.astro.umd.edu/sbnhtml/.

TABLE 1

Log of the Observations for Sycorax

Date and Filter	Exposure (s)	UT	Air Mass	Magnitude
1999 Oct 8:				
R	80	23:41:37.210	1.052	20.404 ± 0.026
R	80	00:04:30.130	1.033	20.447 ± 0.022
R	70	00:27:03.560	1.023	20.432 ± 0.022
B	300	00:31:39.030	1.022	21.764 ± 0.029
V	80	00:39:10.840	1.021	20.752± 0.025
I	80	00:44:14.550	1.021	19.815 ± 0.021
R	70	00:49:21.380	1.022	20.447 ± 0.020
R	70	02:45:36.780	1.161	20.480 ± 0.031
B	300	02:50:14.170	1.173	21.812 ± 0.030
V	80	02:57:38.700	1.193	20.800 ± 0.022
I	80	03:02:37.590	1.208	19.863 ± 0.021
R	70	03:07:28.890	1.223	20.448 ± 0.025
R	80	03:47:31.370	1.386	20.421 ± 0.036
R	80	04:07:50.470	1.501	20.436 ± 0.033
1999 Oct 9:				
R	120	23:43:27.090	1.047	20.458 ± 0.035
R	120	00:06:17.240	1.030	20.407 ± 0.029
R	120	00:28:17.050	1.022	20.419 ± 0.046
R	120	00:53:16.650	1.023	20.391 ± 0.020
R	120	01:17:19.370	1.034	20.433 ± 0.024
R	200	01:40:47.210	1.054	20.421 ± 0.025
B	500	01:47:33.150	1.062	21.915 ± 0.031
V	150	01:58:24.400	1.076	20.903 ± 0.025
I	150	02:04:32.810	1.086	19.966 ± 0.022
R	200	02:10:43.380	1.096	20.457 ± 0.016
R	200	03:00:34.960	1.214	20.450 ± 0.017
R	200	03:25:09.110	1.302	20.450 ± 0.020
R	200	03:49:51.190	1.419	20.410 ± 0.024

The instrumental *b*, *v*, *r*, and *i* have been transformed into standard Johnson *B* and *V* and Cousin *R* and *I* magnitudes by using fitting coefficients (color term and zero point) derived from observations of the standard field T Phoenicis and Mark A stars from Landolt (1992) at the beginning and the end of the night after including exposure-time normalization and air-mass corrections. Aperture correction has also been applied. The transformations are given by the following equations:

TABLE 2

Log of the Observations for Caliban

Date and Filter	Exposure (s)	UT	Air Mass	Magnitude
1999 Oct 8:				
R	600	00:59:10.500	1.024	21.949 ± 0.024
B	1200	01:22:37.740	1.029	23.659 ± 0.049
V	800	01:35:08.840	1.046	22.423 ± 0.033
R	600	01:52:00.450	1.064	21.954 ± 0.036
I	800	02:05:33.450	1.083	21.440 ± 0.024
R	600	02:22:24.310	1.113	21.897 ± 0.036
1999 Oct 9:				
R	800	00:34:52.990	1.021	21.832 ± 0.053
R	800	00:59:19.070	1.025	21.970 ± 0.045
R	800	01:23:16.540	1.039	22.039 ± 0.039
R	800	02:18:08.040	1.112	21.821 ± 0.038
R	800	03:07:55.570	1.243	21.802 ± 0.036
R	800	03:32:22.580	1.339	21.924 ± 0.040
R	800	03:56:58.850	1.468	22.004 ± 0.063

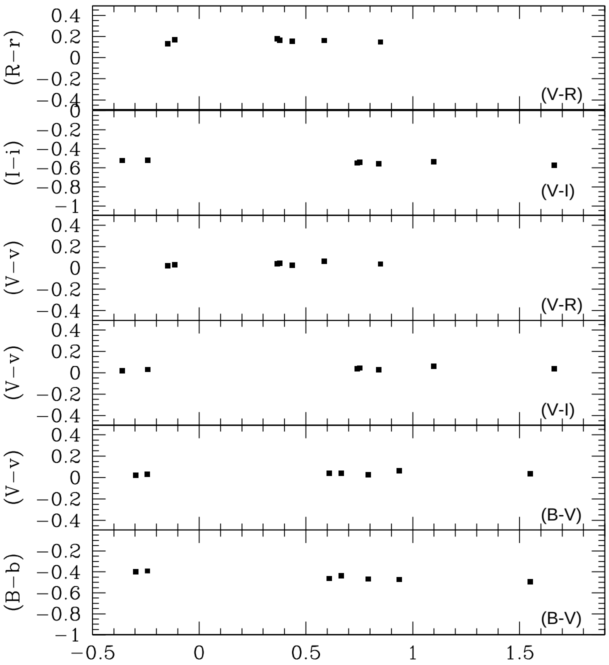

Fig. 1.—Color equations for the night of 1999 October 8

$$B - b = -0.050(B - V) - 0.414 , \quad (1)$$

$$V - v = 0.010(B - V) + 0.030 , \quad (2)$$

$$B - V = 0.994(b - v) - 0.437 , \quad (3)$$

$$V - v = 0.010(V - I) + 0.029 , \quad (4)$$

$$V - I = 1.003(v - i) + 0.551 , \quad (5)$$

$$V - v = 0.020(V - R) - 0.029 , \quad (6)$$

$$R - r = 0.01(V - R) + 0.157 , \quad (7)$$

$$V - R = 1.010(v - r) - 0.101 . \quad (8)$$

These transformations are plotted in Figure 1. The errors affecting this calibration are expected to be on the order of 0.03 mag. All the magnitudes obtained on the second night were translated into the first night through comparison of a group of common field stars in the same frames as the satellites.

3. COLORS

The observations allowed us to obtain the colors of both satellites with excellent accuracy, and we reported them in Table 3, together with corresponding error bars. By looking at $B-V$, the colors are almost similar for both satellites even if Sycorax appears to be bluer than Caliban, and we can make a comparison with other minor bodies of the solar system. They clearly appear less red than most of the Kuiper belt objects, as can be seen on the histogram of $V-R$ reported by Luu & Jewitt (1996), while there is an interesting similarity with some Centaurs, 1995 GO, 1997 CU_{26}, and 1995 DW_2, as is clearly shown in Table V of Davies et al. (1998).

However, it is difficult to provide even a rough interpretation of the colors measured for Sycorax and Caliban. By looking at the histograms of Luu & Jewitt (1996) the $V-R$ values of the satellites could be considered the bluest Kuiper belt objects or the reddest near-earth asteroids, not

TABLE 3

COLORS OF SYCORAX AND CALIBAN

Satellite	$B-V$	$V-R$	$R-I$	$B-R$	$V-I$
Sycorax......	1.012 ± 0.038	0.482 ± 0.042	0.455 ± 0.030	1.494 ± 0.036	0.937 ± 0.031
Caliban......	1.236 ± 0.059	0.473 ± 0.048	0.510 ± 0.043	1.709 ± 0.054	0.983 ± 0.041

forgetting that 0.5 is the value found for most of the comet nuclei and the Trojans. The small number of Centaurus objects observed up to now show a broad range of $V-R$ values, and it might be much too easy to associate Sycorax and Caliban with this group, even if the heliocentric distance of Uranus is comparable to the length of their semimajor axis.

4. LIGHT CURVES

Light curves have been obtained in the R band with exposure times of 600–800 s for Caliban and 80–200 s for Sycorax. The time-dependent part of the light curves, together with a sinusoidal fit described below, is plotted in Figure 2.

Only the first night was photometric, but for both satellites the first night alone is not sufficient to say anything conclusive about the time variability, even applying simple models. So the data of the second night have been translated to the first night by matching the magnitude of common stars in the frames. The chosen stars do not exhibit significant brightness variations; however, this procedure may have left some residual systematic calibration error within a 1 σ level ($\approx$0.03 mag), equivalent to a shift in the zero point of the magnitude scale for the second night relative to the scale of the first night. Since data generally are not evenly distributed about the mean, it is not possible to remove this shift by subtracting the average from the data of each night. As a consequence, a possible small shift in the zero point of the magnitude scale between different nights must be accounted for by the fit itself, adding another degree of freedom to the model. So the model to fit is

$$R(t) = R_0 + \Delta\,\mathrm{U}(t - t_0) + A \sin\left[\frac{2\pi}{P}(t - t_0) + \phi\right], \quad (9)$$

where the four free parameters are the average magnitude, R_0, the amplitude, A, the period, P, and the phase, ϕ. The origin of time, t_0, is assumed to be 2000 October 8 at UT 00:00. The step function U is null during the first night and +1 during the second one. The free parameter Δ accounts for the possible shift in the zero point between the two nights. If this is the case, Δ will assume values significantly different from zero. The fit is performed twice by the method of weighted least squares, the first time imposing $\Delta \equiv 0$ and the second time leaving it as a fifth free parameter. The results of the two fits are then compared. As shown below, the Sycorax data require a significant shift between the first and the second night, while the Caliban data do not. In principle more sophisticated methods could be used, but our limited data set does not justify their application. As a consequence the light curve parameters, particularly their periods, shall be considered only indicative estimates rather than firm results.

On the first night Caliban did not display a large variation ($\Delta R = 0.057 \pm 0.032$ mag, i.e., less than 2 σ), while on the second one it showed $\Delta R = 0.237 \pm 0.045$ mag, corresponding to an $\approx$5 σ level. The first concern was to verify whether such variability may be explained by random fluctuations due to noise or not. The χ^2 test rejected the hypothesis of random fluctuations. In fact by taking into account the data of both nights the significance level for this hypothesis is less than 0.005%. In the case of Caliban no significant shift is required between the magnitude-zero points of the first and second nights. Leaving the shift Δ as a free parameter does not improve the fit, but it reduces the number of degrees of freedom and so the significance level for the fit. Then we imposed $\Delta \equiv 0$ to obtain the best fit for $P = 2.6624 \pm 0.0130$ hr, $\phi = 4.2607 \pm 0.1637$ rad, $A = 0.1169 \pm 0.0102$ mag, and $R_0 = 21.9128 \pm 0.0112$ mag, with $\chi^2 = 2.6331$, equivalent to the significance level SL = 75.63%.

Indeed, most of the information in this estimate is based on the data of the second night. As a comparison, the best fit obtained by considering only the second-night data is the one obtained for $P = 2.7011 \pm 0.0093$ hr, $\phi = 5.1269 \pm 0.1061$ rad, $A = 0.1342 \pm 0.0128$ mag, and $R_0 = 21.9126 \pm 0.0120$ mag, with $\chi^2 = 0.1739$, equivalent to the significance level SL = 98.17%. Note that a better fit is obtained for the second-night data than is obtained for the full data set, the worst-behaving point being the last of the first night. If this point is removed we obtain $P = 2.6678 \pm 0.0119$ hr, $\phi = 4.4204 \pm 0.1428$ rad, $A = 0.1268 \pm 0.0171$ mag, and $R_0 = 21.9037 \pm 0.0120$ mag, with $\chi^2 = 0.6860$, equivalent to the significance level SL = 98.37%. This fact suggests either a residual mismatch in the zero-point calibration between the two nights or that

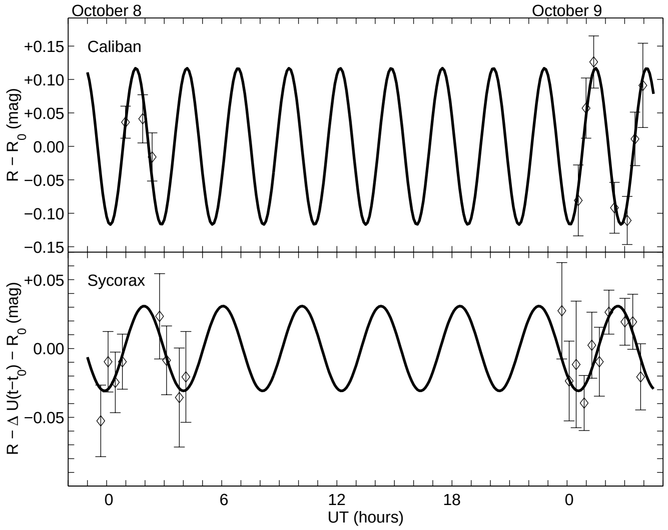

FIG. 2.—Caliban and Sycorax light curves. The nonsinusoidal terms of equation (9) have been subtracted from both light curves to show the time variability. Therefore R_0 has been removed from the Caliban light curve, while $R_0 + \Delta U(t - t_0)$ has been removed from the Sycorax light curve.

the light curve is not properly represented by a sinusoidal time dependence. However, it is not possible to discriminate between these two possibilities from the data as none of the related CCD frames display evident peculiarities. So the difference between the two results will be regarded as an estimate of the systematic errors in the determination of the light curve parameters.

In conclusion our best estimates are $P = 2.66^{+0.04}_{-0.00} \pm 0.01$ hr, $\phi = 4.26^{+0.87}_{-0.00} \pm 0.16$ rad, $A = 0.134^{+0.000}_{-0.008} \pm 0.010$ mag, and $R_0 = 21.913^{+0.000}_{-0.000} \pm 0.011$ mag, in which the first error refers to the systematic error and the second to the random (1 σ) error.

For Sycorax we had more data better distributed in time than for Caliban, but with respect to the errors the photometric variation was smaller. The first night Sycorax displayed $\Delta R = 0.076 \pm 0.027$ mag, while in the second one, $\Delta R = 0.067 \pm 0.026$ mag, both below the 3 σ level. So we cannot claim a more reliable positive detection of significant brightness variation in the Sycorax data, and any attempt to estimate a period would be considered tentative, although during the second night the data hinted at a possible *sinusoidal* variation. Indeed, the hypothesis of random fluctuation over a time-constant brightness explains the observed light curve and fits the Sycorax data better than Caliban data, but the significance level for such a fit is only 55.6%, making this hypothesis hard to support. Moreover, the R magnitudes for the reference stars in the Sycorax frames for the first night are stable, with an rms better than 0.005 mag and a significance level for the hypothesis of a constant magnitude better than 99.99%. Both these observations support (but do not prove) the hypothesis that the detected variability in Sycorax data could be physically significant. So we applied the sinusoidal fit shown in Figure 2.

In the case of Sycorax a nonnull shift $\Delta = (-2.6 \pm 1.3) \times 10^{-2}$ mag shall be allowed in order to have a good fit, consistent with the average photometrical error of the tabulated measures, ≈ 0.027 mag. On the contrary, the imposition of $\Delta \equiv 0$ reduces the significance level for the fit by about a factor of 3. Apart from the method described here, we attempted different ways to get rid of this shift, all producing similar results about the estimate of the period, phase, and amplitude for the light curve. Our conclusion is that the shift must be considered a relevant parameter regarding the minimization of χ^2 only. Of course, since it affects in the same way all the data taken on the same night, the shift is not relevant for the color determination, since colors are obtained from neighboring data.

Taking the data of both nights into account, the best fit was obtained for $P = 4.1156 \pm 0.0416$ hr, $\phi = 4.8750 \pm 0.2594$ rad, $A = 0.0308 \pm 0.0084$ mag, and $R_0 = 20.4566 \pm 0.0103$ mag, with $\chi^2 = 4.9796$ and SL = 97.6%. This represents our best guess for the Sycorax period. The repetition of the fit by using only the second-night data gives instead $P = 3.6841 \pm 0.0406$ hr, $\phi = 0.1679 \pm 0.3303$ rad, and $A = 0.0320 \pm 0.0083$ mag, with $\chi^2 = 2.3487$ and SL = 88.5%. Note that A is not affected by the change, which instead affects the period and phase. In addition the significance is higher when all the data are used to perform the fit, suggesting that all the data have the same statistical significance. At last R_0 from the second-night data only is $R_0 = 20.4322 \pm 0.0053$ mag, whose difference from the R_0 obtained from the full night is dominated by Δ. After correcting for this shift and adding in square the two random errors we obtain $R_0 = 20.4062 \pm 0.0140$ mag. In conclusion for Sycorax we obtain $P = 4.12^{+0.00}_{-0.43} \pm 0.04$ hr, $\phi = 4.88^{+0.00}_{-4.71} \pm 0.25$ rad, $A = 0.032^{+0.001}_{-0.000} \pm 0.008$ mag, and $R_0 = 20.457^{+0.000}_{-0.001} \pm 0.010$ mag.

5. CONCLUSIONS

On the nights of 1999 October 8 and 9 we carried out accurate multicolor observations of Uranus' irregular satellites Sycorax (S/1997 U1) and Caliban (S/1997 U2), providing magnitudes in B, V, R, and I bands. The colors we obtained confirm the values suggested by Gladman et al. (1998). They are redder than those of Uranus and its regular satellites, and Sycorax appears to be bluer than Caliban and most of the Kuiper belt objects.

We obtained light curves in the R band for both satellites, and we estimated periods and amplitudes by fitting the data with a sinusoid. Caliban's light curve displayed significant fluctuations (5 σ), which were not evident in the Sycorax data.

For Caliban, we suggest a light curve period of about 2.7 hr with an amplitude of about 0.13 mag, which is compatible with the rotation periods of the Kuiper belt objects (Romanishin & Tegler 1999). However, the limited number of points and time coverage coupled with calibration uncertainties suggest we be conservative and consider this result as only a first estimate requiring further observations to be confirmed.

Although the data for Sycorax did not show so large a photometric variation, we tentatively provide an estimate of the light curve period and amplitude, which also have to be considered preliminary, about 3.7–4.1 hr and 0.03 mag, respectively. Better time coverage, together with very accurate photometry, may help to unravel a more reliable light curve period for Sycorax.

The authors wish to acknowledge the anonymous referee for valuable suggestions and comments. This work has been partially supported by the Astronomical Technology Group of the Trieste Astronomical Observatory.

REFERENCES

Brown, W. R., & Luu, J. X. 1997, Icarus, 126, 218

Christie, W. 1930, PASP, 42, 253

Cruikshank, D. P., & Brown, R. H. 1986, in Satellites, ed. J. A. Burns & M. S. Matthews (Tucson: Univ. Arizona Press), 836

Davies, J. K., McBride, N., Ellison, S. L., Green, S. F., & Ballantyne, D. R. 1998, Icarus, 134, 213

Gladman, B. J., Nicholson, P. D., Burns, J. A., Kavelars, J. J., Marsden, B. G., Williams G. V., & Offut, B. W. 1998, Nature, 392, 897

Kuiper, G. 1961, in Planets and Satellites, ed. G. Kuiper & B. M. Middlehurst (Chicago: Univ. Chicago Press), 575

Landolt, A. U. 1992, AJ, 104, 372

Luu, J., & Jewitt, D. 1996, AJ, 112, 2310

Pollack, J. M., Burns, J. A., & Tauber, M. E. 1979, Icarus, 37, 587

Romanishin, W., & Tegler, S. C. 1999, Nature, 398, 129

Smith, B. 1984, in Uranus and Neptune, ed. J. T. Bergstralh (NASA CCP-2330) (Greenbelt, MD: NASA), 213

Stetson, P. B. 1991, DAOPHOT II Users Manual (Victoria: Dominion Astrophys. Obs.)