THE ASTROPHYSICAL JOURNAL, 351:277–286, 1990 March 1

THE PERSISTENT COMA OF COMET P/SCHWASSMANN-WACHMANN 1

DAVID JEWITT
Institute for Astronomy, University of Hawaii
Received 1989 June 23; accepted 1989 August 30

ABSTRACT

Time-series photometry of Comet P/Schwassmann-Wachmann 1 in both 1987 and 1988 shows that this comet is continually active despite its large heliocentric distance ($R \sim 6$ AU). The observed activity, upon which the famous outbursts of this comet are superposed, may be driven by the sublimation of crystalline water ice at the nucleus surface. A simple model which accounts for both the continuous activity and the sporadic outbursts is suggested.

Subject headings: comets

I. INTRODUCTION

Comet P/Schwassmann-Wachmann 1 (SW1) possesses orbital and physical properties which distinguish it from all other known comets. Its current orbit is large (semimajor axis ~6.04 AU), nearly circular (eccentricity ~0.04), and slightly inclined to the ecliptic (inclination ~9°.4). The entire orbit of the comet lies between the orbits of Jupiter and Saturn. Gravitational perturbations by the major planets (especially Jupiter) cause a chaotic evolution of the orbit (e.g., Carusi *et al.* 1985) so that, on a time scale of 10^4 yr, the comet orbit will change beyond recognition. Indeed, significant changes in the orbit have occurred even since SW1 was discovered in 1927. It is expected that SW1 will eventually either be captured by Jupiter into a smaller orbit, or, more likely, ejected from the solar system by Jupiter on a hyperbolic orbit. Rickman (1985) discusses the possibility that SW1 is merely the largest of many comets in the Jupiter–Saturn region.

The physical properties of SW1 are no less striking than the orbital properties. The comet is famous for its spasmodic "outbursts," short-duration events in which the total brightness is reported to increase by 5–6 mag, only to fade back to the original "quiescent" level on a time scale of a few weeks (e.g., Roemer 1958, 1966; Whipple 1980). The frequency of the events is poorly known. Typically, 2–3 outbursts are reported per year, but this is surely a lower limit to the true rate, because the observational sampling is incomplete. In between outbursts, the comet is supposed to lose much of its coma and may be visible as a bare or nearly bare nucleus (e.g., Degewij and Tedesco 1982). In "quiescence," the comet was described by Roemer (1958) as "not far from stellar." The quiescent photographic magnitude is generally given as $m_{pg} \sim 18$–19 (Roemer 1958), corresponding to red magnitudes $m_R \sim 17$–18. Emission lines from gaseous CO^+ have been detected both in and out of the outburst state (Cochran, Barker, and Cochran 1980; Larson 1980), but emissions from the radicals which dominate the spectra of comets at smaller heliocentric distances, (e.g., CN, C_2) have not yet been reported. Cowan and A'Hearn (1982) argued that the outbursts could be driven by the equilibrium sublimation of near-surface volatiles (e.g., CO_2) and that the storage of energy postulated in previous outburst models was not needed. Cochran, Cochran, and Barker (1982) mapped the spectrum of the coma during outburst and reported that the wavelength dependence of the reflectivity could be explained by two populations of Mie scattering grains having narrow, submicron size distributions. Cruikshank and Brown (1983) reported a detection of thermal emission from the nucleus and have deduced the diameter (40±5 km) and geometric albedo ($g_v \sim 0.13 \pm 0.04$) of this body. Whipple (1980) used the morphology of the coma to estimate the rotation period (5 days) and pole direction (ecliptic latitude +19° and longitude 280° [epoch 1950]) of the nucleus.

In this paper, we discuss new spatially and temporally resolved photometry of SW1 taken in an extended time period in 1987 and 1988. Most previous photometry of SW1 has been taken using either human retinas or photographic emulsions as detectors (see Whipple 1980 and Degewij and Tedesco 1982 for references to many of the earlier data). Neither type of detector is well suited to the photometry of faint, extended sources such as the coma of SW1. The present study exploits the high quantum efficiency of charge-coupled device (CCD) imagers, and so is more sensitive to low-surface-brightness coma than previous studies. This is the first study to be based exclusively on linear, digital images of relatively high sensitivity and uniform quality.

II. OBSERVATIONS

a) Images

Charge-coupled device images of SW1 were obtained on 45 nights in 1987 and 1988, using the 1.3 m and 2.4 m telescopes of McGraw Hill Observatory, Kitt Peak. The images were recorded using the MASCOT, BRICC, and Mk III cameras. The MASCOT and Mk III cameras contain reducing optics to optimize the image scale on the CCD, while the BRICC contains only a bare CCD exposed at the telescope focal plane (Luppino 1989). Observations in 1987 June–July were taken in parallel with a program of observations of Hyperion by Jim Klavetter, while those in 1988 were taken in parallel with comet and asteroid programs with Jane Lüu.

Flat field calibration images were obtained by exposing the CCD to a uniform twilight sky field. Bias frames were recorded periodically throughout each night. Dark emission from the various CCDs was found to be negligible in the 5–10 minute integrations typically used for SW1. Photometric calibration of the SW1 images was obtained using observations of standard stars from Landolt (1983) and Christian *et al.* (1985). Nightly extinction and zero point corrections were determined from these stars observed at a variety of airmasses. Images taken on nights of cirrus or other light extinction were calibrated photometrically using field stars recorded in subsequent images taken at the next available photometric night. Checks were made to ensure that the extinction caused by clouds was neutral (to minimize differential magnitude errors due to the use of reference stars having colors different from that of SW1). The night-to-night consistency of the photometry is believed to be good at the ± 0.03 mag level for point sources near magnitude $m_R \sim 17$. The photometric uncertainty associated with the measurement of SW1 (an extended source) is larger than the point source uncertainty because of the increased significance of small errors in the background subtraction. Error estimates are listed with the photometry.

The Mould R filter was used for the bulk of this photometric monitoring program. Integration times (generally 300–600 s) were selected according to the instantaneous motion of the comet with respect to field stars. Trailing of the comet with respect to field stars was kept below 1″ in order to simplify the subsequent photometry using small apertures. No dependence of the photometry on the integration time was noticed, showing that trailing effects can be ignored at the level of accuracy of the present data. On a few occasions (e.g., 1988 August 10), shorter than normal integrations were forced by the high central brightness of SW1. The seeing for the observations was generally near 2″–2″.5 full width at half maximum (FWHM) at the 2.4 m and 1″.5–2″ FWHM at the 1.3 m.

Spatial photometry of the images was obtained using a set of synthetic apertures, each centered on the photocenter of the comet. Photometry based on apertures smaller than 2″.5 radius is subject to errors caused by variable atmospheric seeing. Photometry based on apertures greater than 20″ radius suffers from major uncertainties due to sky background subtraction errors. Therefore, photometric data were extracted from the images using apertures with radii in the 2″.5–20″.0 range. Specifically, seven circular apertures of radii 2″.5, 3″.75, 5″.0, 7″.5, 10″.0, 15″.0, and 20″.0 were used for all measurements except those from the summer of 1987, when only the 5″.0 and 10″.0 radius apertures were used. The use of multiple apertures allows us to monitor spatial variations in the coma as a function of time. The sky background was determined from a concentric annulus having inner and outer radii 20″.0 and 30″.0, repectively, and from discrete areas located far from SW1. As we note below, the outer coma actually covers a major fraction of the surface of the CCD in some images. However, the photometric error resulting from coma contamination of the sky position is small (few × 0.01 mag), because the outer coma has extremely low surface brightness compared to the regions sampled by the above photometry apertures.

For simplicity, in this paper we list only the magnitudes determined within the 5″ and 10″ radius apertures [denoted m_R(5″) and m_R(10″), respectively]. The essence of our findings is clearly conveyed by these two numbers. Furthermore, we list only the nightly mean magnitude within each aperture, since little photometric variation occurs within the nightly observing runs. For each night, m_R(5″) was used to compute the annular magnitude m_R(5″–10″) defined by

$$m_R(5''\text{–}10'') = m_R(5'') - 2.5 \log (10^{0.4\Delta m} - 1) , \quad (1)$$

where $\Delta m = m_R(5'') - m_R(10'')$. Physically, we use m_R(5″) to provide a measure of the light scattered by the nucleus plus the near nucleus coma, while m_R(5″–10″) measures a surrounding region of pure coma. The angular scale at the time of the observations was approximately 3600 km arcsec^{-1}.

TABLE 1

GEOMETRIC PARAMETERS OF SW1

UT Date	R (AU)	Δ (AU)	α
1987 Jun 1	5.91	5.33	8°.5
1987 Jul 1	5.90	4.99	4.8
1987 Aug 1	5.89	4.88	0.6
1988 Jun 1	5.82	5.67	10.0
1988 Jul 1	5.82	5.22	8.6
1988 Aug 1	5.81	4.90	4.7
1988 Sep 1	5.81	4.81	1.3
1988 Oct 1	5.80	5.00	6.5
1988 Nov 1	5.80	5.41	9.4
1988 Dec 1	5.79	5.89	9.6

Representative CCD images of SW1 are shown in Figure 1 (Plate 7). The parameters of the comet at the times of each image are given in the figure legend. We found that the appearance of the coma (especially the apparent radius) is strongly affected by the brightness of the night sky, with the coma appearing smaller and more circular on bright sky nights. This effect is a result of the low surface brightness of the outer coma—when the sky is bright, the outer coma becomes lost in the sky noise and the apparent radius is small. The images in Figure 1 were taken on nights having reduced interference from moonlight, so that variations in the morphology of the coma apparent in the figure are real. Figure 1 emphasizes our most basic finding: that comet SW1 displayed an extended coma on all dates of observation.

Geometrical circumstances of SW1 are listed in Table 1. The nightly mean magnitudes determined from the CCD images are listed in Tables 2 and 3 and are plotted as a function of time in Figure 2.

b) Spectra

Spectra of SW1 were taken on UT 1988 June 16, 17, 25, 26, 27, August 5, 8, 9, and September 8. The Mk III spectrograph was used with a 300 line mm^{-1} grating blazed at 5000 Å and covering the approximate wavelength range $4800 \leq \lambda \leq 7100$ Å. A 400 × 576 pixel Thomson CCD was employed as the detector. A 2″.8 wide slit gave the effective spectral resolution $\Delta\lambda \sim 18$ Å, FWHM. The spectra all showed a continuum devoid of molecular emission features and slightly reddened with respect to the Sun. A single example, from UT 1988 September 8 06:50, is presented in Figure 3.

The plotted spectrum is a 1000 s integration, divided by the spectrum of the solar analog star 16 Cyg B and normalized to unity at $\lambda = 6000$ Å. The slope of the continuum is given by S'(4800 Å, 7100 Å) = 12 ± 2% per 1000 Å, or about 0.12 mag redder than the sun in $m_V - m_R$.

III. DISCUSSION

Several features of the images and light curve of SW1 are worthy of note.

1. *Every* CCD image of SW1 taken in the 1987 and 1988 observing seasons shows a strong coma in the vicinity of the nucleus. The morphology of the coma changes from week to week and month to month, but the coma is *always* present in our images. Independent reports by visual and other observers in 1987 May, June, October and 1988 May, June, August, September, October, and December (*IAU* Circulars 4385, 4412, 4471, 4503, 4606, 4637, 4655 and 4689) confirm and extend the documented persistence of the activity in 1987–

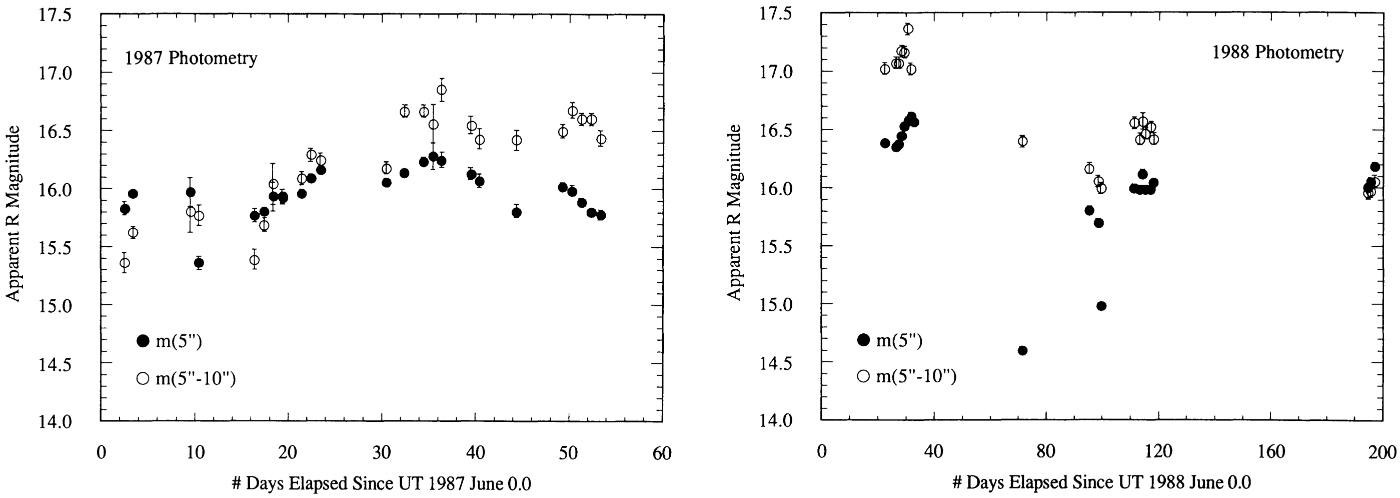

FIG. 2*a* FIG. 2*b*

FIG. 2.—The $m_R(5'')$ and $m_R(5''–10'')$ magnitudes are plotted vs. date of observation. (*a*) Data from 1987. (*b*) Data from 1988. Uncertainties in the $m_R(5'')$ magnitudes are generally too small to be seen at the scale of the figure. Note two outbursts in $m_R(5'')$ in 1988 August and September (day numbers 71 and 99).

1988. The observed activity lacks the impulsive character of the outbursts previously reported in this comet (e.g., Degewij and Tedesco 1982). The steady or persistent coma apparently represents a mode of activity in SW1 qualitatively different from the famous impulsive outbursts. Indeed, several outbursts appear *superposed* upon the persistent coma (e.g., see UT 1987 June 10 [day 10 in Table 2 and Fig. 2*a*] and UT 1988 September 7 [day 99 in Table 3 and Fig. 2*b*]), emphasizing the morphological distinction between the two modes of activity.

2. The coma is asymmetric and amorphous (see Figs. 1 and 4), with few indications of the angular momentum spiral structures sometimes reported in the outburst state (Roemer 1958). Our CCD spectra show that the observed coma consists of dust, with only a scattered, reddened solar continuum and no evidence for molecular emission bands at this time (Fig. 3). The previously detected bands of CO^+ occur at wavelengths too short to be sampled by the Mk III spectra, however.

3. The extent of the coma is considerable. Figure 4 (Plates 8–10) contains three renditions of a single CCD image of SW1 at increasingly harsh contrasts. The surface brightness of the outer coma in Figure 4*c* is near $\Sigma \sim 26–27$ mag arcsec^{-2} or less than 1% of the brightness of the night sky. The apparent diameter of the coma at this surface brightness is $\sim 100''$, corresponding to $\sim 4 \times 10^5$ km at the comet, in the plane of the sky. The true linear dimension of the coma must be greater still, because the anti-solar (tail) dimension suffers from extreme

TABLE 2

1987 PHOTOMETRY

UT Date	Day Number[a]	m_R (5″)	m_R (10″)	m_R (5″–10″)
1987 Jun 02.47	02.47	15.83±0.06	14.82±0.06	15.36±0.09
1987 Jun 03.42	03.42	15.96±0.03	15.02±0.04	15.62±0.05
1987 Jun 09.47	09.47	15.97±0.12	15.12±0.13	15.80±0.18
1987 Jun 10.40	10.40	15.36±0.06	14.79±0.06	15.77±0.09
1987 Jun 16.39	16.39	15.77±0.06	14.81±0.06	15.39±0.09
1987 Jun 17.42	17.42	15.80±0.04	14.99±0.04	15.69±0.06
1987 Jun 18.34	18.34	15.93±0.12	15.23±0.13	16.04±0.18
1987 Jun 19.33	19.33	15.92±0.04	15.17±0.05	15.93±0.06
1987 Jun 21.44	21.44	15.96±0.04	15.27±0.04	16.09±0.06
1987 Jun 22.40	22.40	16.09±0.04	15.43±0.04	16.29±0.06
1987 Jun 23.41	23.41	16.16±0.04	15.45±0.04	16.25±0.06
1987 Jun 30.43	30.43	16.06±0.03	15.36±0.04	16.18±0.05
1987 Jul 02.40	32.40	16.14±0.03	15.62±0.04	16.67±0.05
1987 Jul 04.39	34.39	16.24±0.03	15.68±0.04	16.67±0.05
1987 Jul 05.40	35.40	16.28±0.11	15.66±0.12	16.56±0.16
1987 Jul 06.35	36.35	16.25±0.07	15.76±0.07	16.85±0.10
1987 Jul 09.40	39.40	16.13±0.05	15.57±0.06	16.55±0.08
1987 Jul 10.36	40.36	16.07±0.06	15.48±0.06	16.43±0.09
1987 Jul 14.31	44.31	15.81±0.06	15.32±0.06	16.42±0.09
1987 Jul 19.25	49.25	16.02±0.04	15.48±0.04	16.50±0.06
1987 Jul 20.27	50.27	15.99±0.04	15.53±0.05	16.68±0.07
1987 Jul 21.23	51.23	15.89±0.03	15.43±0.04	16.60±0.05
1987 Jul 22.28	52.28	15.80±0.03	15.38±0.04	16.60±0.05
1987 Jul 23.27	53.27	15.78±0.04	15.31±0.05	16.44±0.06

[a] Numbers of days since UT 1987 June 0.0 (see Fig. 2)

TABLE 3

1988 PHOTOMETRY

UT Date	Day Number[a]	m_R (5″)	m_R (10″)	m_R (5″–10″)
1988 Jun 22.44	22.44	16.39 ± 0.03	15.91 ± 0.04	17.03 ± 0.05
1988 Jun 26.43	26.43	16.35 ± 0.03	15.90 ± 0.04	17.07 ± 0.05
1988 Jun 27.45	27.45	16.38 ± 0.03	15.92 ± 0.04	17.07 ± 0.05
1988 Jun 28.44	28.44	16.45 ± 0.03	16.00 ± 0.04	17.17 ± 0.05
1988 Jun 29.42	29.42	16.53 ± 0.03	16.05 ± 0.04	17.17 ± 0.05
1988 Jun 30.41	30.41	16.58 ± 0.03	16.15 ± 0.04	17.36 ± 0.05
1988 Jul 01.44	31.44	16.62 ± 0.03	16.05 ± 0.04	17.02 ± 0.05
1988 Jul 02.44	32.44	16.57 ± 0.03	...	...
1988 Aug 10.27	71.27	14.60 ± 0.03	14.41 ± 0.04	16.40 ± 0.04
1988 Sep 03.23	95.23	15.81 ± 0.03	15.22 ± 0.04	16.16 ± 0.05
1988 Sep 06.33	98.33	15.70 ± 0.03	15.11 ± 0.04	16.05 ± 0.05
1988 Sep 07.26	99.26	14.98 ± 0.03	14.62 ± 0.04	15.99 ± 0.05
1988 Sep 19.10	111.10	16.00 ± 0.03	15.49 ± 0.04	16.56 ± 0.05
1988 Sep 21.10	113.10	15.99 ± 0.03	15.43 ± 0.04	16.42 ± 0.05
1988 Sep 22.10	114.10	16.12 ± 0.04	15.57 ± 0.06	16.57 ± 0.07
1988 Sep 23.10	115.10	15.99 ± 0.03	15.45 ± 0.04	16.47 ± 0.05
1988 Sep 25.10	117.10	15.99 ± 0.03	15.47 ± 0.04	16.52 ± 0.05
1988 Sep 26.10	118.10	16.04 ± 0.03	15.46 ± 0.04	16.42 ± 0.05
1988 Dec 11.56	194.56	16.01 ± 0.03	15.23 ± 0.04	15.96 ± 0.05
1988 Dec 12.48	195.48	16.06 ± 0.03	15.26 ± 0.04	15.97 ± 0.05
1988 Dec 13.80	196.80	16.19 ± 0.03	15.37 ± 0.04	16.06 ± 0.05

[a] Number of days since UT 1988 June 0.0 (see Fig. 2)

foreshortening at the small phase angles of observation (typically only a few degrees; see Table 1).

4. The $m_R(5'')$ magnitudes show nonrandom variations about a mean near $m_R(5'') \sim 16.0$–16.5, in data sequences taken 1987 June–July, 1988 June, and 1988 September. The variations are structured with an approximate period near 6 days. The persistence of this brightness oscillation at three epochs in two consecutive years suggests that it is a fundamental property of the comet, not just a transient response to irregular activity on the nucleus. The obvious possibility that the oscillation is caused by the rotation of the underlying nucleus is discussed in § III*b*.

5. The differential magnitude $\Delta m = m_R(5''–10'') - m_R(5'')$ provides a measure of the degree of central condensation of the image of SW1. Figure 5 shows that Δm varies substantially with time. Note that a steady state coma (with a $1/p$ surface brightness law, where p is the impact parameter) would have $\Delta m = 0$, while steeper surface brightness laws correspond to larger Δm. The systematic increase in Δm seen in the photometry from 1987 represents a progressive fading of the coma with respect to the central light. This fading may also be seen in Figure 2. Variations in Δm are less orderly in 1988, with several excursions to large Δm caused by outbursts in SW1. It is likely that long-term evolution of the active areas on the nucleus of SW1 affects Δm.

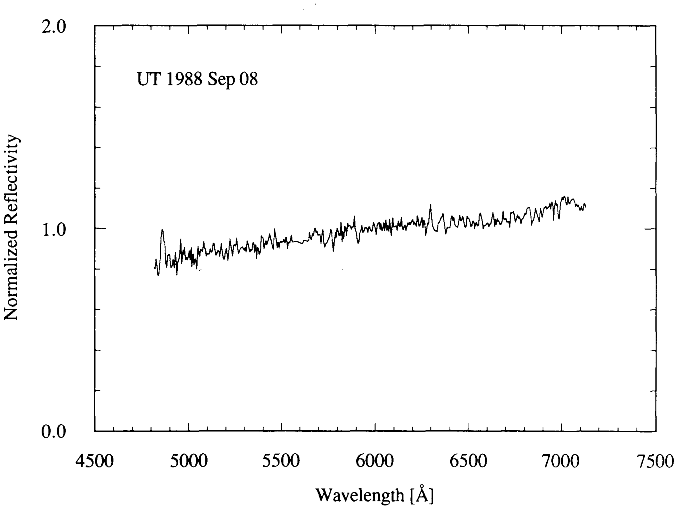

FIG. 3.—CCD spectrum of SW1 taken UT 1988 September 08, with the Mk III spectrograph at the 2.4 m telescope. The spectrum, which has been normalized to the spectrum of a solar analog star, is devoid of molecular emission features. The spectrum of SW1 consists of only scattered solar continuum at this date.

6. The velocity of expansion of the coma may be estimated from the photometry. Sudden brightness changes ("outbursts") are apparent on UT 1987 June 10 and UT 1988 September 7. Spatially resolved photometry of the second of these "outbursts" is plotted in Figure 6. The mean surface brightness within each of the concentric annuli is plotted from nightly means of the photometry from UT 1988 September 3, 6, and 7. The outburst clearly began after the observations on the night of the 6th, and was first observed as a brightening of the inner apertures on the night of the 7th. Careful examination of the figure shows that the ejected material has propagated out to the $p = 5''$ radius, corresponding to a linear distance $x \sim 1.75 \times 10^4$ km. Since the outburst began within 1 day of its first detection, the grain speed is necessarily $v \geq 1.75 \times 10^4$ km/1 day ~ 0.2 km s^{-1}. This velocity is compatible with the Bobrovnikoff/Delsemme velocity for $R = 5.8$ AU, namely, $v_{BB} = 0.58\ R^{-0.5}$ (km s^{-1}) = 0.24 km s^{-1} (Delsemme 1982) and is similar to velocity estimates based on photographic images of expanding coma structures (e.g., Roemer 1958).

7. The faintest $m_R(5'')$ in our data is $m_R(5'') \sim 16.5$ mag, about 1.5–2.5 mag *brighter* than the faintest photographic "nuclear" magnitudes reported in the literature (e.g., Roemer 1958; Degewij and Tedesco 1982). There are two probable reasons (a color term and a geometric term) for this discrepancy.

First, the published nuclear magnitudes are generally pho-

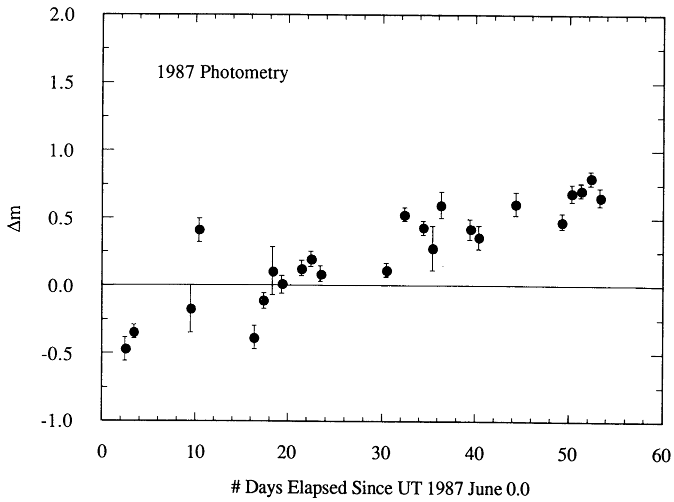

FIG. 5*a*

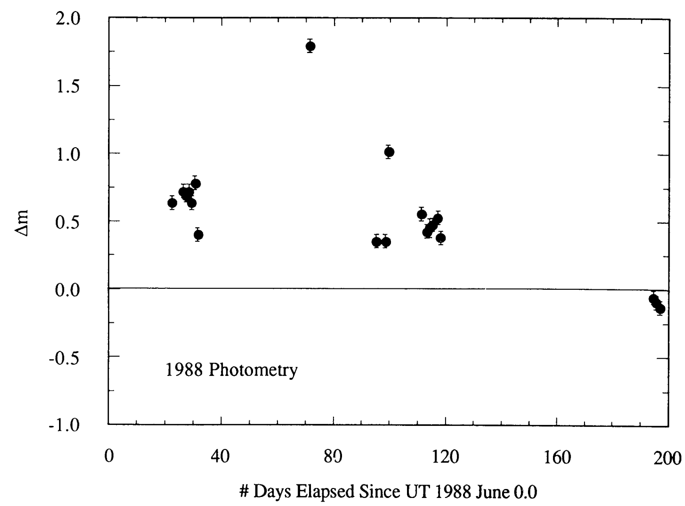

FIG. 5*b*

FIG. 5.—Plot of $m_R(5''–10'') - m_R(5'')$ vs. date of observation (data taken from Tables 2 and 3). (*a*) Data from 1987. (*b*) Data from 1988. Systematic variations in the magnitude difference, especially well seen in the 1987 data, indicate long-term changes in the radial profile of the coma.

tographic or blue magnitudes ($\lambda_{\text{eff}} \sim 4000–4500$ Å), whereas we observed in the red ($\lambda_{\text{eff}} \sim 6500$ Å). For the Sun, $m_B - m_R = 1.17$ mag (Allen 1973), and SW1 is further reddened with respect to the Sun by 0.2–0.4 mag in $m_B - m_R$ (Kiselev and Chernova 1979), giving $m_B - m_R \sim 1.4–1.6$ mag for SW1. The color-corrected magnitude discrepancy is thus reduced from 1.5–2.5 mag to $\sim$0–1 mag.

Second, the published nuclear magnitudes were, on average obtained at larger heliocentric and geocentric distances (say $R \sim 7$ AU, $\Delta \sim 6$ AU) than the present photometry ($R \sim 5.8$ AU, $\Delta \sim 5.0$ AU). This is true both because the present observations were taken near perihelion, and because the orbit of SW1 has undergone systematic contraction during the past few decades (Carusi *et al.* 1985). The differences in R and Δ correspond approximately to a decrease in magnitude of 0.8. Therefore, the magnitude discrepancy is further reduced to a few tenths of a magnitude, or about the level of accuracy of photographic photometry on a moving object this faint. In this sense, there is no contradiction between the faintest CCD magnitudes from the present study and the faintest photographic nuclear magnitudes in the published literature.

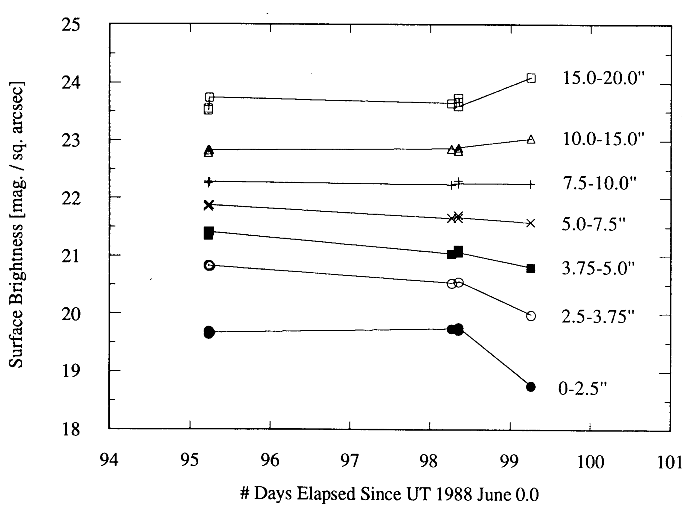

FIG. 6.—Surface brightness of the coma determined UT 1988 September 3, 6, 7. Inner and outer radii of the annuli used to compute the surface brightness are marked in the figure. An "outburst" occurred between September 6 and 7. The ejected material has propagated to radial distances $p \sim 5''$ (17,500 km) in a time ≤ 24 hr, implying velocity $v \geq 200$ m s^{-1}.

The *detailed* comparison of the present photometry with photometry published in the literature is problematic, however. The published photometry is difficult to interpret because, with few exceptions, the photometry is given without reference to the size of the effective diaphragm used to obtain the photometry. The magnitude of an extended object has exact physical significance only when accompanied by an explicit reference to the region of the object which is measured. Most such photometry is in fact obtained using photographic emulsions and human retinas, in which case it is not clear that the effective diaphragm can ever be specified. All that we can reasonably conclude is that there is little evidence in the literature to suggest that SW1 has ever been observed to be fainter than the typical $m_R(5'')$ of the present study (Tables 2 and 3), once color and geometrical terms are taken into account.

a) The Persistent Coma

The persistence and relative constancy of the extended coma in SW1 suggest continuous mass loss from the nucleus throughout the period of observation. Impulsive mass loss from a single outburst would produce a coma which dissipates and fades on the diaphragm crossing time, τ_d. The diaphragm crossing time (in hours) is given by

$$\tau_d \approx 0.35\, p\, \Delta\, R^{0.5}\,, \qquad (2)$$

where p [arcsec] is the radius of the photometry diaphragm, R [AU] is the heliocentric distance, and Δ [AU] is the geocentric distance. In equation (2), we have assumed the Bobrovnikoff/Delsemme relation (Delsemme 1982) for the velocity of the coma particles. With $p = 5''$ and $R \sim 6$ AU, $\Delta \sim 5$ AU, we obtain $\tau_d \sim 21$ hr, or about 1 day. The accuracy of equation (2) is confirmed by the spatially resolved photometry (observation #6 in § III and Fig. 6), which clearly shows a photometric response to mass-loss variations occurring on time scales $\sim \tau_d$. Clearly, an impulsive event could not produce the observed coma, which is sustained for months or years (the interval between the first and last observations listed in Tables 2 and 3 is about 500 days). What, then, could be the cause of the steady persistent coma? In view of our knowledge of the high water abundance in other comets (e.g., P/Halley), it is natural to first seek an explanation in terms of the sublimation of water ice from the nucleus of SW1, even though SW1 is widely regarded as being too far from the Sun (and therefore, too cool) for water sublimation to be effective.

The rate of loss of mass from the nucleus may be crudely estimated from the photometry, according to the procedure described in Jewitt and Lüu (1989). For example, in 1988 June, the persistent coma magnitude was $m_R(5''\text{–}10'') \sim 17$. The geometric cross section corresponding to this magnitude is $C \sim 1.3 \times 10^9$ m^2, assuming a geometric albedo of 0.04 for the grains. If this cross section is ascribed to grains of radius $a \sim 0.5$ μm (see Cochran, Cochran and Barker 1982) and density $\rho = 1000$ kg m^{-3}, we can readily calculate the mass of the grains projected in the 5″–10″ annulus as $M \sim 6 \times 10^5$ kg. Dividing by the diaphragm crossing time (eq. [2]), we estimate the order of magnitude mass-loss rate

$$dM/dt \sim 10 \text{ kg s}^{-1} . \qquad (3)$$

We calculate the water ice mass fluxes using a very simple equilibrium sublimation model, in which the insolation is balanced by losses due to radiation and sublimation from the surface of SW1. We write

$$\frac{F_{\text{sun}}(1 - A)}{R^2} = \chi\left(\epsilon\sigma T^4 + L\,\frac{dm}{dt}\right), \qquad (4)$$

in which $F_{\text{sun}} = 1360$ [W m^{-2}] is the solar constant, R [AU] is the heliocentric distance, A is the Bond albedo of the active area, $\epsilon \sim 1$ is the emissivity of the active area, $\sigma = 5.67 \times 10^{-8}$ [W m^{-2} K^{-4}] is the Stefan constant, T[K] is the temperature of the active area, $L = 2 \times 10^6$ [J kg^{-1}] is the latent heat of sublimation of water ice, dm/dt is the specific mass-loss rate [kg m^{-2} s^{-1}] due to sublimation, and χ is the secant of the solar incidence angle, averaged over the active area. In this first-order calculation, we neglect thermal conduction into the interior, since the conductivity of the nucleus is likely to be small. Equation (4) is solved using the temperature dependence of the water sublimation rate given by Washburn (1926). As a limiting case, we take $\chi = 1$, corresponding to a plane active area located at the subsolar point and perpendicular to the incident solar radiation. The best estimate of the nucleus Bond albedo is $A = 0.08$, which is the Bond albedo found by multiplying the $g_v = 0.13 \pm 0.04$ geometric albedo of Cruikshank and Brown (1983) by their adopted phase integral (0.6). We suspect that the 0.08 Bond albedo may be high, because observations of other cometary nuclei generally give geometric albedos several times smaller than g_v as quoted by Cruikshank and Brown. Equation (4) was also solved using $A = 0.04$ and $A = 0.16$, to examine the dependence of the solution on the adopted Bond albedo.

The water ice mass fluxes computed from equation (4) are plotted versus heliocentric distance in Figure 7. At present, SW1 has perihelion and aphelion distances $q = 5.7$ AU and $Q = 6.3$ AU, respectively. These distances are marked in the figure. Near perihelion, the specific mass-loss rate resulting from sublimation of crystalline ice with $A = 0.08$ is $dm/dt \sim 10^{-7}$ kg m^{-2} s^{-1}. The model dm/dt will tend to be overestimated because we have neglected conduction of heat into the interior of the nucleus and underestimated because we have

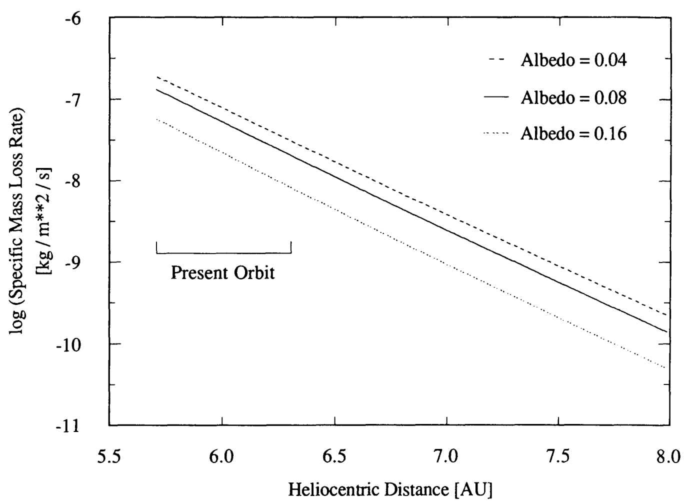

FIG. 7.—Specific mass-loss rate due to equilibrium sublimation of crystalline water ice vs. heliocentric distance (see eq. [4]). The range of heliocentric distances spanned by SW1 in its present orbit is marked. At the time of the present observations, the expected mass-loss rate is of order 10^{-7} kg m^{-2} s^{-1}.

neglected topographical trapping of radiation (as inferred on asteroids from the beaming parameter; e.g., Spencer, Lebofsky, and Sykes 1989). In the absence of more exact knowledge of the physical properties of the nucleus, it is difficult to decide which of the above two effects might be dominant. At the level of uncertainty imposed by uncertainties in the albedo, emissivity, conductivity, spin rate, and nucleus obliquity, $dm/dt \sim 10^{-7}$ kg m^{-2} s^{-1} provides an order of magnitude estimate of the sublimation rate of an exposed water ice surface.

The 10 kg s^{-1} production rate estimated from the photometry could be supplied by sublimation of water ice from an area on the nucleus $\sim 10^8$ m^2, or about 2% of the surface area of a 20 km radius spherical nucleus. The small fraction of the total surface area which is inferred to participate in the sublimation is reminiscent of better studied nuclei (e.g., see the review by A'Hearn 1988). A nonvolatile mantle shields nucleus ices from direct illumination on these nuclei and probably also on SW1. Furthermore, these sublimation fluxes are large enough to lift grains of radius $a \leq 3$ μm from the nucleus of SW1 against nucleus gravity, consistent with the presence of micron-sized grains in the coma (Cochran, Cochran, and Barker 1982). Thus, it seems very plausible that relatively small areas of water ice on the surface of SW1 can adequately explain the persistent coma apparent in our CCD images from 1987 and 1988. Of course, we have no *proof* that water ice is responsible; the persistent coma could be produced equally well by low-level activity in a more volatile ice. However, in view of the common abundance of water in all other studied nuclei, it is quite appealing to adopt a hypothesis as simple as the water ice one. The idea that water ice might sublimate at $R \sim 6$ AU is not unprecedented in the study of comets; the coma of comet P/Halley first appeared at $R \sim 6$ AU and was attributed to the sublimation of water (Wyckoff *et al.* 1986; Meech, Jewitt, and Ricker 1986).

Independent evidence compatible with the presence of a perpetual coma in SW1 includes the detection of CO^+ emission both inside (Cochran, Barker, and Cochran 1980) *and* outside (Larson 1980) outburst periods. We interpret the CO as being liberated by the steady sublimation of the crystalline water ice matrix (see Bar-Nun *et al.* 1985 for an experimental account of the trapping of volatiles in water ice). Possibly related is the large, but extremely uncertain, production rate of hydrogen reported by Festou and Atreya (1982).

The continuous presence of a water-driven coma in 1987 and 1988 begs the question "is SW1 *always* active?". Clearly, a definitive answer to this question cannot be given until we possess time-resolved CCD photometry extending over one or more complete orbits. However, it seems likely that SW1 *is* always measurably active and that the persistent coma reported here is especially prominent because of the proximity of SW1 to perihelion. Near perihelion, the surface temperature of the SW1 nucleus is a maximum, and the water sublimation rate is highest. The persistent coma is likely to be at maximum strength, and it is therefore now more readily detectable than at any other position in the orbit. However, the orbital variation in the mass flux from a water ice nucleus moving in the current orbit of SW1 is only a factor ~ 10 from perihelion to aphelion (see Fig. 7). A mass loss rate 10 times smaller than that in equation (3) would still produce an observable dust coma. A faint coma has often been reported even in photographic observations in the quiescent state (Roemer 1958; Degewij and Tedesco 1982). It is probable that modern detectors, with their greater sensitivity, will show a coma at all times in the vicinity of the nucleus of SW1, albeit weaker than the coma present near perihelion in 1987 and 1988. A specific prediction of the water sublimation model of the persistent coma is that SW1 will display a coma at all positions in the orbit when observed with equipment comparable in sensitivity to that employed here.

b) The 6 Day Variations

The persistently oscillatory nature of the $m_R(5'')$ photometry suggests rotation of the nucleus of SW1. It is obvious from the extended images (e.g., Figs. 1 and 4) that the *bare* nucleus cannot be detected in our data. However, it is possible that the nucleus contributes a significant fraction of the total light in the smallest ($2''.5$) aperture, and that the rotation of the nucleus modulates the brightness of the coma in a periodic fashion. This inference would be consistent with the rotation pole proposed by Whipple (1980) in that the angle between the line of sight and the predicted rotation pole is presently large (about 60°). Furthermore, the ~ 6 day period of the variations in $m_R(5'')$ is long compared to the diaphragm crossing time ($\tau_d \sim 1$ day), so that the cyclic variations are unlikely to be a simple artifact of transient activity in the coma. In SW1, the photometric variations could be due to the nucleus directly or to rotational modulation of the rate of sublimation from discrete active areas (as in P/Halley). Whipple (1980) inferred a 5 day rotation period in SW1 from a model of the expansion of the coma applied to visual and photographic observations. The same model has given incorrect periods when applied to comets for which the rotation period was measured by independent, more direct methods (e.g., Jewitt and Meech 1988; Jewitt and Lüu 1989; Lüu and Jewitt 1989). Nevertheless, the similarity between Whipple's period and the ~ 6 day structure seen in Figure 2 is intriguing.

String-length and harmonic analyses of the photometry in Tables 2 and 3 do not yield any formally significant period of variation. We believe that pure periodicity in the light from the rotating nucleus of SW1 is hidden by short-term variations in the strength of the near-nucleus coma. An attempt was made to correct for these variations using the surface brightness of the coma in the radial distance range $5'' \leq p \leq 15''$ to estimate the coma contribution in the inner apertures, and then to use this estimate to isolate the signal from the nucleus alone. The correction failed to improve the shape of the light variations in the central magnitudes and did not improve the significance of the periodicity seen there. Presumably, the surface brightness profile is too steep or too irregular to be accurately extrapolated to the region of the nucleus. Hence, we conclude that the present observations are insufficient for us to either prove or disprove that the central photometric variations are the result of a rotating nucleus.

Regardless of the specific interpretation placed on the variations in the central magnitudes, we can use these magnitudes to place an upper limit to the albedo times cross section product of the nucleus. The faintest apparent magnitude in our data is $m_R(5'') \sim 16.5$ (1988 June), at $R = 5.82$ AU, $\Delta = 5.25$ AU, and $\alpha = 8^\circ.7$. Adopting a phase coefficient $\beta = 0.04$ mag deg^{-1}, the derived absolute magnitude is

$$m_R(1, 1, 0) \geq 8.7 , \qquad (5)$$

corresponding to a geometric albedo times cross section product $g_r C \leq 290$ km^2. This is consistent (within the uncertainties) with the value of the same quantity deduced from IR observations by Cruikshank and Brown (1983), namely $g_r C = (0.13 \pm 0.04)\pi(20 \pm 2.5)^2 = 160 \pm 50$ km^2. The albedo times cross section products for other nuclei are typically 1 km^2 (Jewitt and Meech 1988), about two orders of magnitude less than for SW1. Since the albedo of SW1 is unlikely to be two orders of magnitude larger than the albedos of other nuclei, it seems inescapable that SW1 has an unusually large nucleus.

c) Cause of the Outbursts

The existence of the persistent coma may provide a new clue concerning the origin of the spasmodic outbursts of SW1. Sublimation of the active surface will steadily exhume volatile subsurface material, exposing it to direct solar heating and making it available to drive the sporadic outbursts. We do not know what the exposed material is (popular candidates include a volatile ice, e.g., Cowan and A'Hearn 1982, or an amorphous ice, e.g., Smoluchowski 1985, Klinger 1985). Regardless of its specific identity, steady sublimation on SW1 provides a simple and natural way to bring the buried material to the vicinity of the surface, and it simultaneously accounts for the observed persistent coma.

At the present time, insufficient data exist to permit a decision strongly in favor of any particular outburst model. However, it is both amusing and illuminating to pursue one line of thought regarding the origin of the outbursts. We suggest that the outgassing properties of SW1, including the spasmodic outbursts *and* the persistent coma, are qualitatively consistent with the presence of near-surface amorphous ice in the nucleus. Our suggestion combines recent work on the thermal properties of amorphous ice (Smoluchowski 1985; Klinger 1985) with evidence for the sublimation of crystalline ice provided by the persistent coma.

Briefly, we speculate that the nucleus of SW1 is composed largely of amorphous water ice and that solar heating has transformed a surface layer (or "crust") into crystalline ice (see Froeschlé, Klinger, and Rickman 1983; Herman and Podolak 1985). Local sublimation of the crystalline ice crust produces the persistent coma and eventually exposes the subsurface amorphous ice to solar heating. The exothermic transformation of the exposed amorphous ice produces an outburst and simultaneously re-seals the crust. Thus, both aspects of the photometric behavior of SW1, the outbursts and the periods of steady, low level activity, are qualitatively accounted for by the model. The major questions concern the thickness of the crystalline crust and the interval between successive outbursts.

We suppose that the nucleus of SW1, prior to its entry into the inner solar system, was composed of amorphous water ice. Amorphous ice is metastable, and at a critical temperature, $T_C \sim$ 140–150 K, spontaneously transforms to a crystalline form, releasing the latent energy ($\Delta E = 9 \times 10^4$ J kg^{-1}) in the process. There is no direct evidence for (or against) amorphous ice in cometary nuclei, but it is the thermodynamically preferred structural form of ice when condensed at low temperatures. Amorphous ice has been detected in the interstellar medium and is readily formed in the laboratory by condensation onto a cold surface (Klinger 1980). Therefore, it seems physically reasonable to suppose that cold cometary nuclei contain amorphous ice.

The temperature in the deep interior of SW1 is $T_{\rm int} < T_C$, so that amorphous ice is thermodynamically stable there (Klinger 1985). In the current orbit, however, amorphous ice at the subsolar point on SW1 will be subject to exothermic transformation, because the equilibrium blackbody temperature at the subsolar point is $T_{\rm BB} = 158$ K $> T_C$. The exothermic phase change from amorphous to crystalline ice will raise the temperature at the surface, causing a sudden increase in the sublimation rate at the surface and simultaneously driving a thermal pulse in to the interior of the nucleus. This thermal pulse may initiate the transformation of deeper regions of amorphous ice, producing a crystalline ice crust which grows from the surface of the nucleus downward. The vertical propagation of the crust will be halted when the thermal pulse encounters ice too cold to be heated to a temperature $T \geq T_C$ by the energy of the phase change. The crystalline crust will grow at local hot spots on the nucleus, especially near the subsolar point and on slopes normal to the incident solar radiation. Over the course of a few orbital periods ($P_{\rm orb} \sim$ 15 yr), the crystalline layer will spread to cover much of the surface of the nucleus (if the obliquity is small, regions near the rotation poles may never attain $T \geq T_C$ and so may resist the phase change).

How thick does the crystalline ice crust grow? To address this question accurately would require a detailed knowledge of the temperature versus depth profile in the nucleus. This profile is a function of physical quantities which are either poorly defined or unknown in SW1, including the porosity, density, conductivity, spin vector, and previous orbital history of the comet (see Bar-Nun, Heifetz, and Prialnik 1989 for a detailed calculation using parameters specific to comet P/Tempel 1). We see little point in constructing a detailed thermal model of SW1 in the presence of these major uncertainties. Therefore, we proceed using a simplistic physical characterization of SW1 and note that our simplistic approach provides an upper limit to the sought-after crustal thickness.

The thermal skin depth for a medium of thermal diffusivity κ [m^2 s^{-1}] heated by a source with period P[s] is

$$z \sim \left(\frac{P\kappa}{\pi}\right)^{0.5} . \quad (6)$$

The thermal diffusivity of amorphous ice at relevant temperatures is $\kappa \sim 10^{-7}$ m^2 s^{-1} (Klinger 1980). The skin depth corresponding to the orbital period $P_{\rm orb} = 15$ yr is $z \sim 10$ m. The temperature at $z \sim 10$ m is approximately equal to the temperature of a spherical blackbody moving in the orbit of the comet $T_{\rm int}$ (Klinger 1985). For SW1, we find $T_{\rm int} \sim 110$ K. The thermal skin depth associated with the diurnal heating of the nucleus is obtained from equation (6) by substituting $P = 6$ days for the likely rotation period (§ III*b* and Whipple 1980). We find a diurnal skin depth $z_0 \sim 0.1$ m. Diurnal thermal effects are confined to a layer several times z_0 in thickness. We approximate the temperature at depths $z \leq 10$ m by

$$T(z) = T_{\rm int} + T_0 \exp\left(-\frac{z}{z_0}\right) , \quad (7)$$

where $T_{\rm int}$ is the temperature of the deep interior ($z \gg z_0$), z_0 is the diurnal skin depth, and $T_0 = T(z = 0) - T_{\rm int}$ is equal to the temperature excess at the nucleus surface resulting from solar heating.

The energy per unit column area released by a phase change to depth Z is just $E_1 = \rho FLZ$, where L [J kg^{-1}] is the energy released per unit mass in the phase change and F is a factor needed to account for the presence of refractory matter (dust) mixed in the ice. Refractory matter absorbs some of the energy of the ice phase change and so will damp the thermal wave driven into the nucleus. The ratio of the production rates of refractory matter (dust) to volatile matter (gas) has been accurately measured in only one comet. McDonnell *et al.* (1989) find a dust to gas production rate ratio $2 \pm 1:1$ in comet Halley. We adopt $F = \frac{1}{3}$, compatible with a 2:1 dust-to-ice ratio in the nucleus of SW1. The energy per unit column area needed to raise the temperature to T_C in a column extending from the surface to depth Z is

$$E = \rho c_p \int_0^Z [T_C - T(z)] dz , \quad (8)$$

where c_p [J kg^{-1} K^{-1}] is the specific heat capacity of amorphous ice. A first-order estimate of the maximum depth to which the phase change will occur is obtained by setting $E_1 = E$. The crust thickness, Z, is then given by solution of the equation

$$0 = [c_p(T_C - T_{\rm int}) - FL]y + c_p(T_C - T_{\rm int})[\exp(-y) - 1] , \quad (9)$$

where $T(0) = T_C$ at the moment of incipient phase transition, and where y is the dimensionless depth, defined as $y = Z/z_0$. Equation (9) gives an *upper limit* to y (and Z), because some of the energy liberated by the phase change will escape from the system through radiation into space and through sublimation, especially in the surface layers. In addition, some of the liberated energy will be used in heating the newly transformed crystalline ice to temperatures above T_C, further reducing y.

With the physical parameters discussed above, the solution of equation (9) gives $y \sim$ 1–5. This result is stable with respect to changes in $T_{\rm int}$ provided $T_{\rm int} \leq 110$ K, which satisfies our estimate above, although only barely. For the sake of argument, we adopt $y \sim 5$ or $Z \sim 0.5$ m as the thickness of the crystalline crust produced by the amorphous to crystalline phase change. The fresh crust will cool on a time scale $t_{\rm cool} \sim \pi Z^2/\kappa_c$, where $\kappa_c = 10^{-6}$ m^2 s^{-1} is the thermal diffusivity of crystalline ice. By substitution, $t_{\rm cool} \sim 7.5 \times 10^5$ s ($\sim$9 days). This cooling time gives a measure of the expected duration of the "outburst" owing to strong sublimation produced by the phase change. The calculated $t_{\rm cool}$ is in satisfactory agreement with published outburst durations of 5 days to a few weeks

(Whipple 1980). Once it has cooled, the sublimation of the crystalline crust proceeds at the linear rate $dr/dt = (dm/dt)/\rho$, where ρ is the density of the crystalline ice and $dm/dt \sim 10^{-7}$ kg m^{-2} s^{-1}. For plausible densities $100 \leq \rho \leq 1000$ kg m^{-3}, the recession rate is 1–10 Å s^{-1}, corresponding to 3–30 mm yr^{-1}. A 0.5 m slab would sublimate on the time scale $t_{\rm sub} \sim Z/dr/dt \sim$ 15–150 yr (or $1P_{\rm orb} - 10P_{\rm orb}$).

Thus, we envision an amorphous ice nucleus sheathed in crystalline ice to an average depth $Z \sim 0.5$ m. Every 1–10 orbits, a given spot on the nucleus will be sufficiently thinned by sublimation to expose amorphous water ice, causing an outburst of a few days duration. The existence of a number of active spots is needed to explain the observed rate of outburst (several per year), but this is compatible with high-resolution images of P/Halley, which show several apparently independent active spots distributed over the surface.

The model is attractive primarily because of its simplicity—only one unproven but physically reasonable assumption (that the nucleus is initially composed of amorphous water ice) is needed. The model accounts for most of the physical quantities of SW1 which can be regarded as known with certainty, including (1) the duration of the outbursts, given in the model by the cooling time of the fresh crystalline ice slab, (2) the presence of a coma between outbursts, a natural result of sublimation from the crystalline ice slab, and (3) the few per year occurrence rate of the outbursts, determined by the rate of sublimation of the crystalline ice slab and by the number of active areas.

Furthermore, the model explains the "unusual" physical character of SW1 as a natural product of its peculiar orbit (see also Froeschlé, Klinger, and Rickman 1983). Situated in a nearly circular orbit at $R \sim 6$ AU, SW1 is at the very edge of the crystalline ice sublimation zone, and at the same time is at the very edge of the amorphous ice stability zone. Comets in circular and low–eccentricity orbits at smaller R have long since lost their near-surface amorphous ice because they are too hot ($T > T_c$). The orbits of the common short period comets are by and large entirely contained within $R \sim 6$ AU, so that any amorphous ice in these nuclei should be depleted. Activity in these comets is presumably controlled by surface sublimation of the crystalline ice. Conversely, comets in circular orbits at larger R are too cold to trigger the amorphous to crystalline phase change, and therefore they fail to exhibit the frequent outbursts shown in SW1. Comets on elliptical orbits which cross the critical $R \sim 6$ AU zone (e.g., P/Halley, P/Brorsen-Metcalf) may also show activity due to amorphous water ice, but this activity will be quickly swamped by sublimation from crystalline ice as the heliocentric distance decreases on the preperihelion leg of the orbit. In SW1, the probable slow rotation rate of the nucleus of SW1 also helps to elevate the subsolar temperature, and it enhances the sublimation rate and phase transition described here. The gradual temporal evolution of the orbit from larger semimajor axes also helps to guarantee a low internal temperature. Most significantly, then, there is no need to invoke special physical characteristics for SW1 to explain its extraordinary physical behavior.

IV. CONCLUSIONS

1. Comet SW1 possessed an extensive coma on each night of observation in the 1987–1988 observing seasons (heliocentric distance range $5.7 \leq R \leq 5.8$ AU). The steady, persistent coma and implied continuous activity stand in sharp contrast to the sporadic "outbursts" for which this comet is famous. The persistent coma constitutes a separate mode of activity in comet SW1.

2. The observed persistent coma may be sustained by a very modest dust mass loss rate $dm/dt \sim 10$ kg s^{-1}. Sublimation from ~ 100 km^2 of dirty water ice (about 2% of the nucleus surface area) could explain the observed coma, provided the ice albedo is low ($A \sim$ a few percent). The strength of the persistent coma may vary with position in the orbit, but sublimation calculations lead us to predict that a detectable coma should be present at all times. Comet SW1 is presently near perihelion, and the coma is likely to be at maximum prominence.

3. Persistent nonrandom variations in the light from the central region of the comet suggest rotation of the underlying nucleus. However, no definitive period can be identified in the present data, probably because of low-level mass ejections which confuse the nucleus light curve.

4. The "unusual" physical character of SW1 may be a natural product of the peculiar orbit (essentially circular at $R \sim 6$ AU) of this comet. At this R, the subsolar temperature is just high enough to promote the sublimation of crystalline water ice (the suggested source of the persistent coma reported here) and is also sufficient to trigger the exothermic amorphous—crystalline phase change (perhaps responsible for the outburst mode of activity). Short-period comets with smaller perihelia ($q \ll 6$ AU) are too hot to contain amorphous ice in the near-surface regions (their mass loss is thus controlled by crystalline ice), while comets with perihelia $q > 6$ AU are too cold either to sublimate or to trigger the phase transition.

The present observations were taken at McGraw Hill Observatory, operated by a consortium including University of Michigan, Dartmouth College and MIT. I thank Jim Klavetter for his assistance with the 1987 observations and Jane Lüu for her assistance with observations in 1988. Matt Johns, Bob Barr, and Larry Bruer provided vital and reassuring support of the telescope electronics, while Gerry Luppino provided useful real-time telephonic advice concerning MASCOT and BRICC problems. This work was supported by a grant from the NASA Planetary Astronomy Program.

REFERENCES

A'Hearn, M. F. 1988. *Ann. Rev. Earth Planet. Sci.*, **16**, 273.
Allen, C. W. 1973, *Astrophysical Quantities* (London: Athlone).
Bar-Nun, A., Herman, G., Laufer, D., and Rappaport, M. L. 1985, *Icarus*, **63**, 317.
Bar-Nun, A., Heifetz, E., and Prialnik, D. 1989, *Icarus*, **79**, 116.
Carusi, A., Kresak, L., Perozzi, E., and Valsecchi, G. B. 1985, *Long-term Evolution of Short Period Comets* (Bristol: Adam Hilger).
Christian, C. A., Adams, M., Barnes, J. V., Butcher, H., Hayes, D. S., Mould, J. R., and Siegel, M. 1985, *Pub. A.S.P.*, **97**, 363.
Cochran, A. L., Barker, E. S., and Cochran, W. D. 1980, *A.J.*, **85**, 474.
Cochran, A. L., Cochran, W. D., and Barker, E. S. 1982, *Ap. J.*, **254**, 816.
Cowan, J. J., and A'Hearn, M. F. 1982, *Icarus*, **50**, 53.
Cruikshank, D. P., and Brown, R. H. 1983, *Icarus*, **56**, 377.
Degewij, J., and Tedesco, E. F. 1982, in *Comets*, ed. L. L. Wilkening (Tucson: University of Arizona Press), pp. 665–695.
Delsemme, A. H. 1982, in *Comets*, ed. L. L. Wilkening (Tucson: University of Arizona Press), pp. 85–130.
Festou, M. C., and Atreya, S. K. 1982, in *Cometary Exploration*, Vol. **1**, ed. T. Gombosi (Budapest: Hungarian Academy of Science), pp. 203–220.
Froeschlé, C., Klinger, J., and Rickman, H. 1983, in *Asteroids, Comets, Meteors*, ed. C. Lagerkvist and H. Rickman (Uppsala: Uppsala University Press), pp. 215–224.
Herman, G., and Podolak, M. 1985, *Icarus*, **61**, 252.
Jewitt, D. C., and Meech, K. J. 1988, *Ap. J.*, **328**, 974.

Jewitt, D. C., and Lüu, J. X. 1989, *A.J.*, **97**, 1766.
Kiselev, N. N., and Chernova, G. P. 1979, *Soviet Astr. Letters*, **5**, 156.
Klinger, J. 1980, *Science*, **209**, 271.
———. 1985, in *Ices in the Solar System*, ed. J. Klinger, D. Benest, A. Dollfus, and R. Smoluchowski (Dordrecht: Reidel), pp. 407–417.
Landolt, A. 1983, *A.J.*, **88**, 439.
Larson, S. M. 1980, *Ap. J.* (*Letters*), **238**, 47.
Luppino, G. A. 1989, *Pub. A.S.P.*, in press.
Lüu, J. X., and Jewitt, D. C. 1989, *Icarus*, submitted.
Meech, K. J., Jewitt, D. C., and Ricker, G. R. 1986, *Icarus*, **66**, 561.
McDonnell, J. A. M., Green, S. F., Nappo, S., Pankiewicz, G. S., Perry, C. H., and Zarnecki, J. C. 1989, preprint.
Rickman, H. 1985, in *Dynamics of Comets: Their Origin and Evolution*, ed. A. Carusi and G. B. Valsecchi (Dordrecht: Reidel), pp. 149–172.
Roemer, E. 1958, *Pub. A.S.P.*, **70**, 272.
———. 1966, *Mem. Soc. Roy. Sci. Liege*, **13**, 23.
Smoluchowski, R. 1985, in *Ices in the Solar System*, ed. J. Klinger, D. Benest, A. Dollfus, and R. Smoluchowski (Dordrecht: Reidel), pp. 397–406.
Spencer, J. R., Lebofsky, L. A., and Sykes, M. V. 1989, *Icarus*, **78**, 337.
Washburn, E. W. 1926, in *International Critical Tables*, Vol. **3** (New York: McGraw-Hill), pp. 210–212.
Whipple, F. L. 1980, *A.J.*, **85**, 305.
Wyckoff, S., Wagner, R. M., Wehinger, P. A., Schleicher, D. G., and Festou, M. C. 1986, *Nature*, **316**, 241.

DAVID JEWITT: Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, HI 96822
[jewitt@hubble.ifa.hawaii.edu]

1990ApJ...351..277J

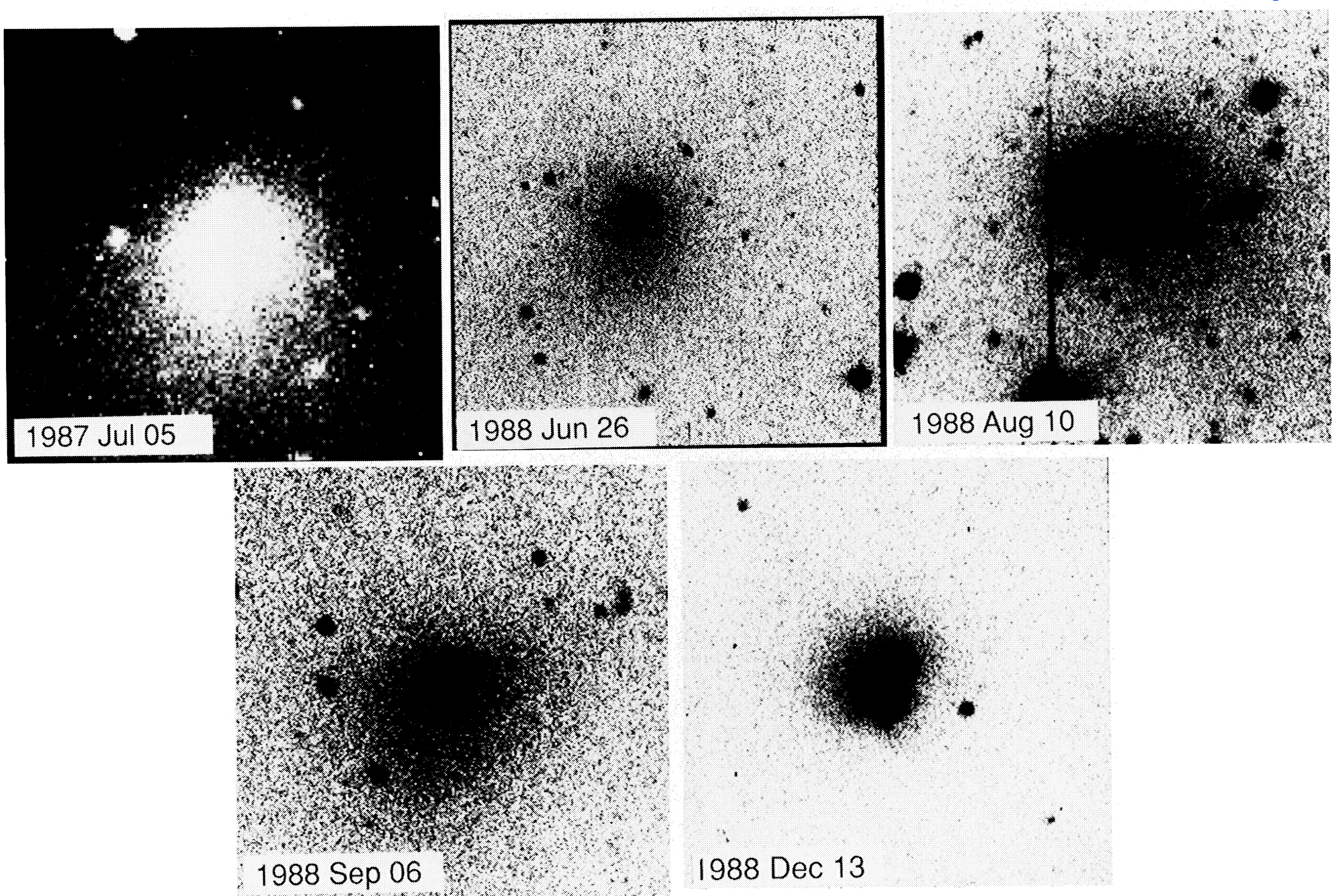

FIG. 1.—Representative CCD images of SW1 from 1987 and 1988. Dates of the images are indicatd in the figure. Each image has north to the top, east to the right, and a width corresponding to 120″, or 4×10^5 km at the comet. The images are 300–600 s integrations through an R filter. Other petinent parameters may be determined by inspection of Tables 1–3.

JEWITT (*see* **351**, 278)

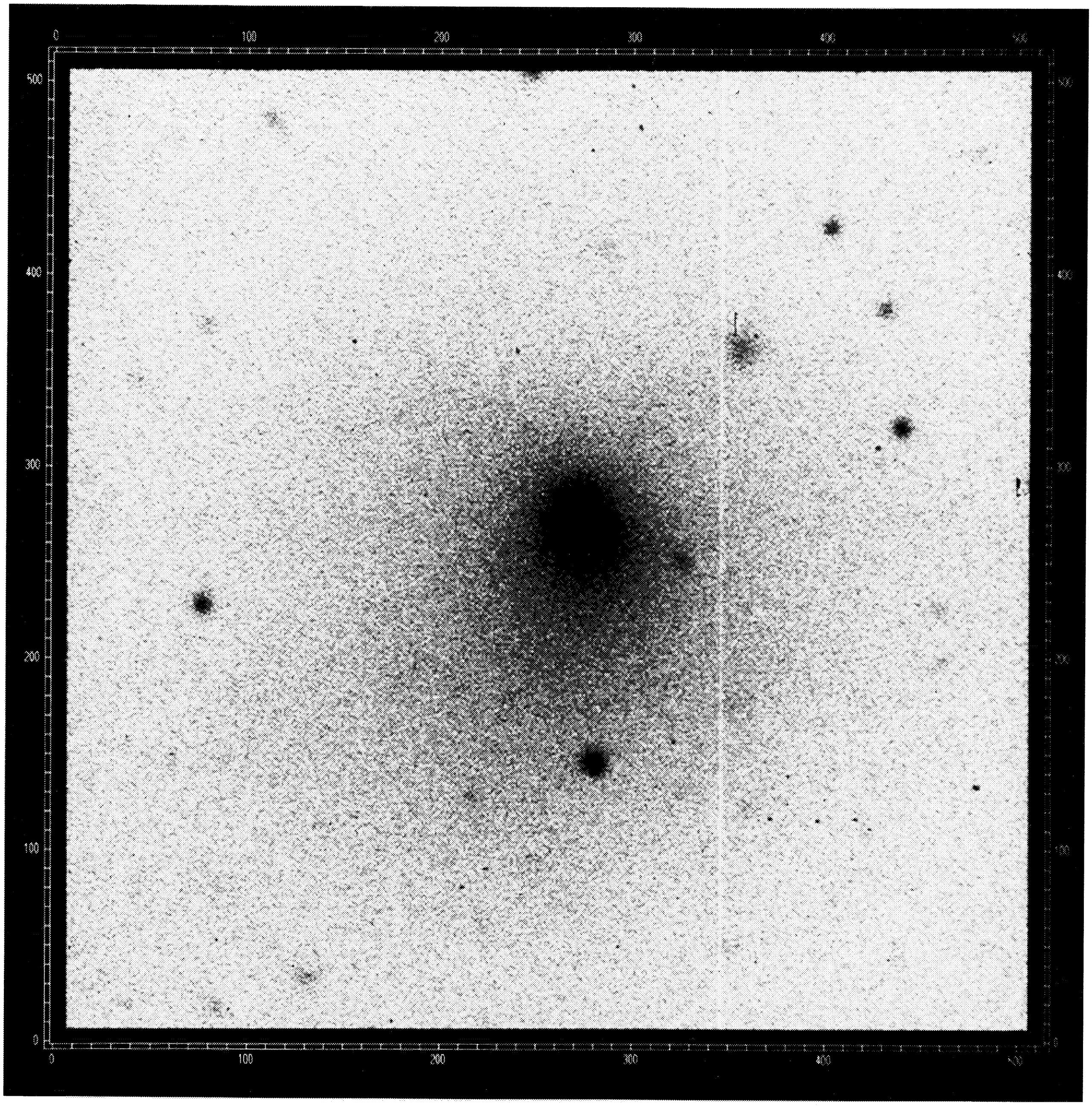

FIG. 4*a*

FIG. 4.—A 600 s Mould *R* filter integration of SW1 taken UT 1988 June 22d 10h 40m using the 2.4 m telescope and the BRICC–ACIS CCD. The image is shown at three contrasts to emphasize the vast extent of the dust coma. The image scale is 0.″25 per pixel. Field of view is 125″ on a side (corresponding to 4.4×10^5 km in the plane of the sky), with N to the top and E to the left.

JEWITT (*see* **351**, 279)

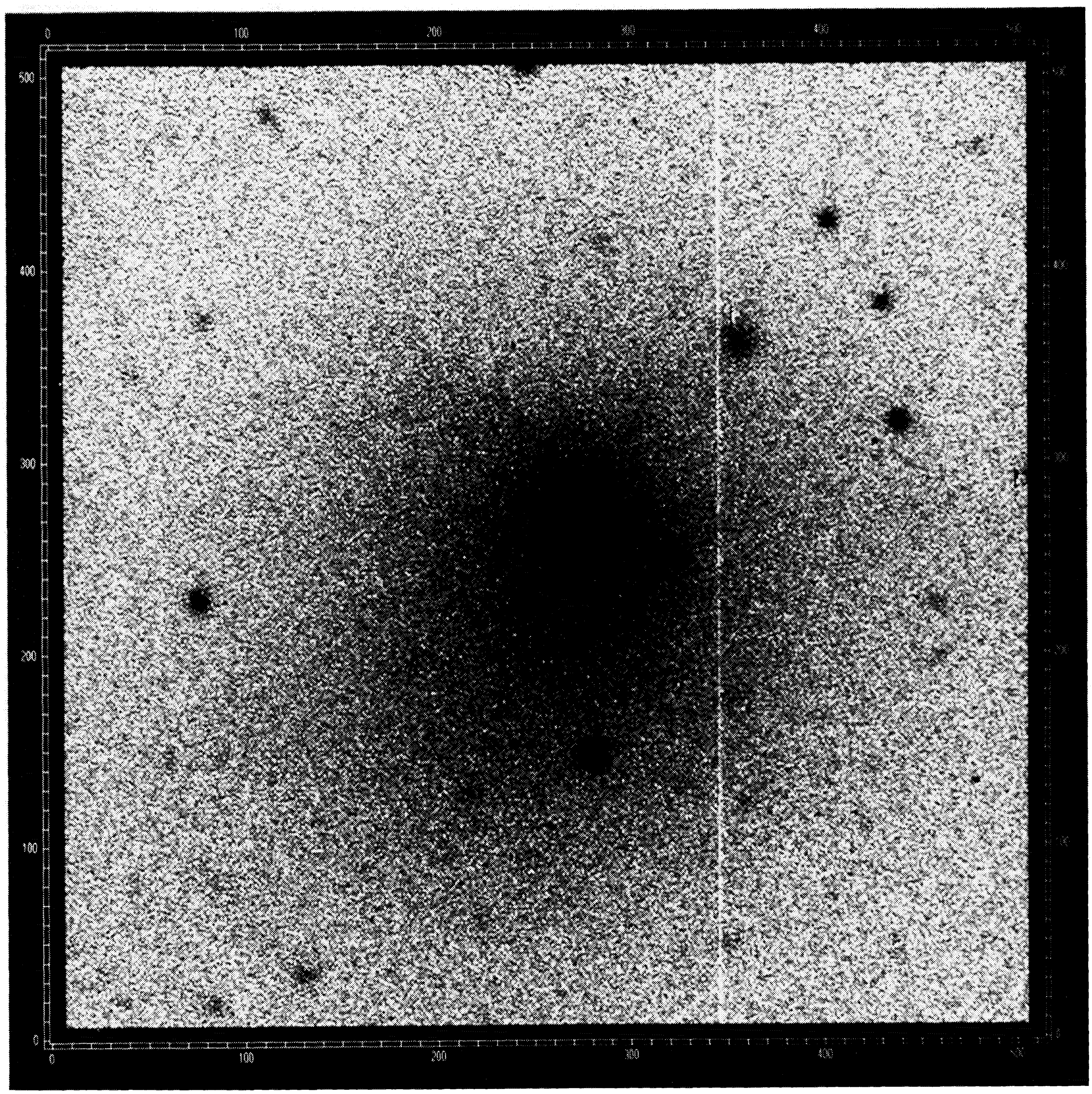

FIG. 4*b*

JEWITT (*see* **351**, 279)

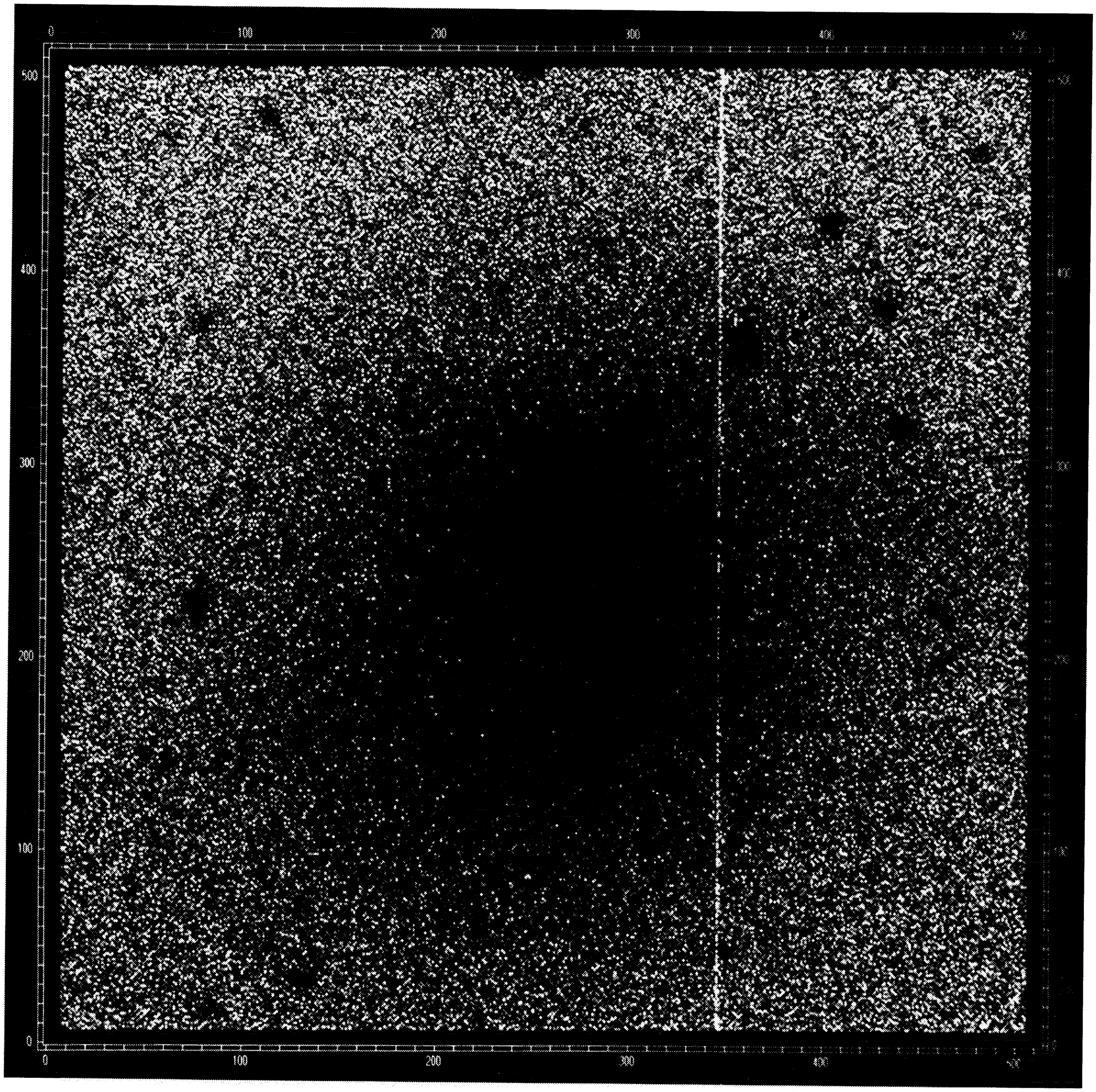

FIG. 4c

JEWITT (*see* **351**, 279)