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ACTIVITY IN COMETS AT LARGE  
HELIOCENTRIC DISTANCE\*

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Almost all that we know of the physical characteristics of comets has been learned from observing objects of moderately small perihelion distance. By far the greatest number of the objects represented in the catalogs of comets and comet orbits were discovered when they were relatively bright and therefore moderately close to the sun and to the earth. Details of structure in the head and tail can be studied only in the brighter comets. An abundance of light is necessary to obtain spectra, especially spectra of moderate or high dispersion, or spectra in the red or ultraviolet. Even direct photography in the relatively narrow bands of radiation that can be attributed to specific molecules or to reflected sunlight is confined to fairly bright comets.

It is well known that the brightness of comets depends strongly upon the heliocentric distance, since the more intense solar radiation at small distances excites the material of the comet to greater activity. A dependence as strong as  $r^{-8}$  or more is by no means unknown.

Although bright comets continue to be the source of most of our present knowledge, an increasing number of comets that remain at large heliocentric distances have been discovered in recent years. Especially have the photographic survey programs carried out with instruments such as the 20-inch Carnegie astrograph of

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the Lick Observatory and the 48-inch Schmidt telescope of the Palomar Observatory contributed discoveries of valuable objects. Most important, some of the comets discovered with these powerful photographic instruments have become bright enough for limited astrophysical investigations. Results already obtained suggest that the smaller objects observed in the region of the terrestrial planets may not be in all ways representative of comets in general.

To demonstrate the need for revised ideas about normal behavior of comets, we will need first to review the characteristics and behavior of a "typical" comet. Then we shall consider some statistics regarding the comets that remain at greater distance from the sun, and especially the importance of recent discoveries. Finally I shall describe the characteristics of several of the known comets of perihelion distance greater than 3.0 a.u. and some of the interesting observations that have been made within the last few years.

#### A TYPICAL COMET

Most known comets have perihelion distances of the order of one astronomical unit. Our ideas of a "typical" comet are prejudiced by this example of observational selection, governed by the way in which the apparent brightness of a comet depends upon its position in space relative to the sun and to the earth.

Differences between individual comets are very great and obvious. Even under similar geometrical circumstances, some comets are very much brighter, and presumably bigger, than others. There are great differences in the degree of central condensation, which probably reflect differences in the size and cohesiveness of the nucleus. Comets differ in the relative amounts of dust and of gas in the head and tail, and vary probably to some extent also in the chemical composition and physical characteristics of the material. The substance of some comets appears to be much more volatile than that of other comets, and some individual comets display activity that probably can be attributed to explosive events within the nucleus.

Even a typical *periodic* comet, for which accurate predictions of position are possible, is rarely observed to a heliocentric dis-

tance greater than 3.0 a.u. Many are lost to observation at even lesser distances. At the distance of the minor planets, 2.5 to 3.0 a.u., an average comet is an object of 19th or 20th magnitude, too faint to show recognizable structure. Cometary characteristics are not striking, and the object may be quite indistinguishable from a minor planet by physical appearance alone. Observers who attempt to follow comets to the limit of detection are well acquainted with the possibility of misidentifications.

If a comet is large and bright enough, the presence of emission from the CN molecule may be recognized at heliocentric distances as great as 3.0 a.u., according to Swings and Haser.<sup>1</sup> At greater distances the light of a comet has been thought to be exclusively reflected and scattered sunlight, but direct observational evidence is not abundant, and there is some suggestion that molecular emission may be present at considerably greater distances. I shall return to this point later.

As the heliocentric distance of the comet decreases, other molecular emissions appear in the head:  $C_3$  and  $NH_2$  appear at about 2 a.u.; the Swan bands of  $C_2$  appear around 1.8 a.u.; and other molecular emissions (OH, NH, CH) are present around 1.5 a.u. In some comets the continuum may still be strong at small heliocentric distances; in others the molecular emission may be overpowering, with the continuum only faintly detectable in the immediate vicinity of the nuclear condensation. At very small heliocentric distances, emissions of metals, Na, and even Fe and Ni, may be detectable. The development proceeds in the reverse sense with increasing heliocentric distance after perihelion passage, the emissions of  $C_3$  and  $NH_2$ , and finally CN, being the last to disappear. Differences in the profiles of bands, especially of CN, are caused by differences in radial velocity of the comet relative to the sun, and therefore by differences in the wavelength of the exciting solar radiation as it impinges on the comet.

The size of the coma varies with heliocentric distance, the greatest diameter being found on the average at about 1.6 a.u.<sup>2</sup> At first the material from the nucleus of the comet volatilizes at a more rapid rate because of the more abundant solar radiation. But as the heliocentric distance decreases still further, the increase in the energy available leads to a decrease in the observable size

of the coma as the molecules dissociate at smaller distance from the nucleus. It must be remembered, however, that the diameter of the coma is a very indefinite observational quantity. Obviously the size measured for the coma on a photograph will depend upon the telescope, the photographic emulsion, the exposure time, the sky brightness, and a host of other factors. The size measured visually is similarly uncertain. It is evident that the boundary must be defined in some specific way, as, for example, the isophote at which the surface brightness has dropped to half the central value.

It has been stated that comets begin to produce tails at heliocentric distances varying from 1.5 a.u. downward.<sup>1</sup> In 1953, G. Merton,<sup>3</sup> in reporting on observations of P/Comas Solá, 1951 *h*, commented on the observation by L. Kresák of a tail 15' long on November 26, 1952: “. . . remarkable, considering that the heliocentric distance was 1.9 a.u.” Since that time ideas of the distances at which comets may have well-developed tails have undergone considerable revision.

Comets moving in nearly parabolic orbits do not differ in any fundamental way from those of the Jupiter family that move in ellipses of short period. Well- and poorly-condensed objects, objects that brighten slowly with decreasing heliocentric distance, and objects that brighten more rapidly may be found among either short-period or parabolic comets. On the average the short-period comets probably tend to be less dusty than those comets which have spent little time in the inner solar system. Nevertheless, there are dusty periodic comets, such as P/Giacobini-Zinner,<sup>4</sup> and gaseous parabolic comets, such as Comet Burnham, 1959 *k*.<sup>5</sup> Oort and Schmidt distinguish between “old” and “new” comets,<sup>6</sup> in at least an average way, on the basis of the rate of brightening with decreasing heliocentric distance, the strength of the continuous spectrum at distances from the sun greater than about 1 a.u., and the rate of deterioration of the comet as a whole.

#### COMETS FAR FROM THE SUN

With the use of increasingly powerful instruments, comets that remain at large distance from the sun even at perihelion are represented in the catalogs in increasing numbers. The impor-

tance of the photographic technique in discovery is especially important, as can be demonstrated by a tabulation of recent comet discoveries, such as that given by Roemer.<sup>7</sup> Of the 40 new comets discovered in the decade from 1950 to 1959, 18 were found by visual search and 22 by photography. It should be emphasized that comets with large perihelion distance are almost invariably found by photography with powerful wide-field instruments. This fact is demonstrated by noting that every one of the comets discovered in the interval 1950–59 with perihelion distance greater than 1.5 a.u., fifteen in all, was discovered by photography.

To turn attention to comets with even larger perihelion distance, let us list in Table I the 17 known objects with perihelion distance greater than 3.0 a.u.

TABLE I

COMETS WITH PERIHELION DISTANCE GREATER THAN 3.0 a.u.

	Comet	$i$	$q$ (a.u.)
1925 II	P/Schwassmann-Wachmann 1	9°5	5.538
1948 III	Johnson	53.2	4.709
1954 V	Abell	123.9	4.501
1957 VI	Wirtanen	33.2	4.446
1960 $e$	Humason	125.4	4.274
1925 VI	Shajn-Comas Solá	146.7	4.181
1942 VIII	Oterma	172.5	4.113
1956 I	Haro-Chavira	79.6	4.074
1729	Sarabat	77.1	4.051
1936 I	Van Biesbroeck	66.1	4.043
1955 VI	Baade	100.4	3.870
1914 III	Neuimin	71.0	3.747
1927 IV	Stearns	87.7	3.684
1934 II	Jackson	141.9	3.486
1942 VII	P/Oterma	4.0	3.405
1905 IV	Kopff	4.3	3.340
1947 VIII	Wirtanen	155.1	3.267

Attention should be directed to the fact that five of these comets were discovered during the past ten years. Of these five, three were found with the 48-inch Schmidt telescope at Palomar, one with the 20-inch Carnegie astrograph of the Lick Observa-

tory, and one with the 26-inch Schmidt of the Tonantzintla Observatory.

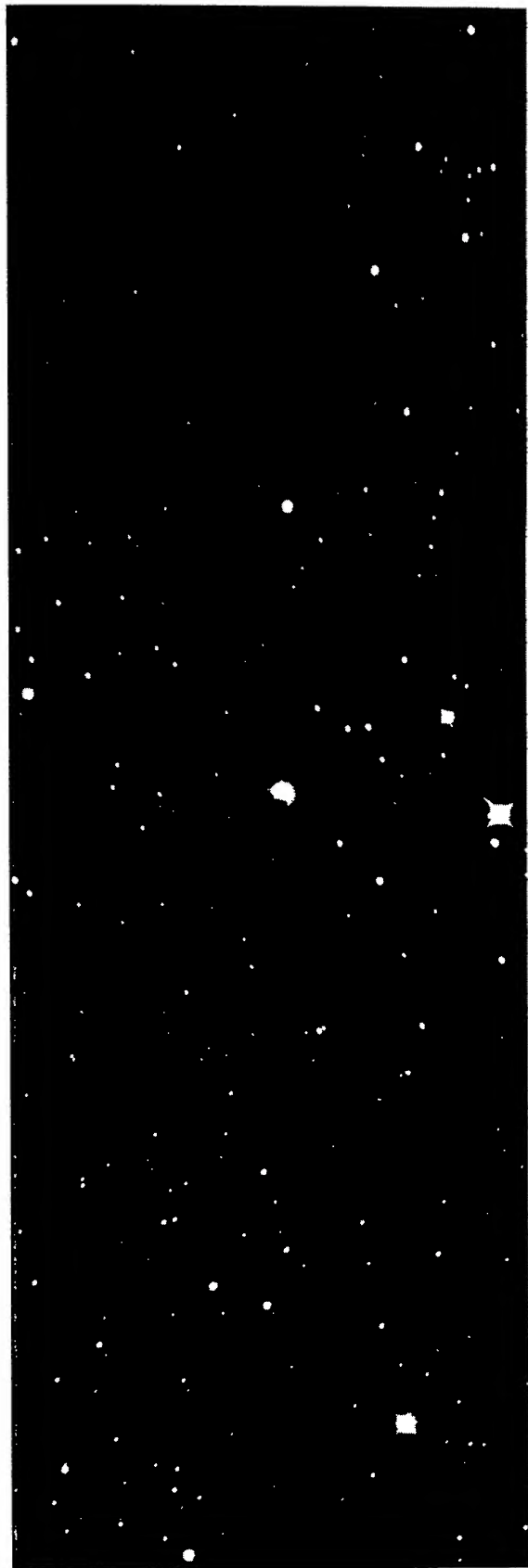
#### OUTBURSTS OF PERIODIC COMET SCHWASSMANN-WACHMANN 1

Of the activity displayed by comets at large heliocentric distance, that exhibited by P/Schwassmann-Wachmann 1 is undoubtedly the best known. This comet moves in a nearly circular orbit at a distance from the sun comparable with that of the planet Jupiter. Normally the comet is of the 18th magnitude, but at irregular intervals it may brighten by as much as five or six magnitudes within an interval of days or hours. Many papers have been devoted to descriptions of outbursts of this comet, studies of possible correlations with solar activity, and speculations as to the physical mechanisms involved. Yet each outburst seems to have its own peculiar characteristics; the question of correlation with solar activity has not been convincingly resolved, and the physical mechanism is still a puzzle. I have previously reviewed work up to 1958 and given a description of an outburst that occurred at the end of August 1957.<sup>8</sup> Observations of more recent outbursts have been given by Götz<sup>9</sup> and by Walker,<sup>10</sup> while Weigert has made a theoretical study of halo formation.<sup>11</sup>

An outburst that took place in the autumn of 1961 was one of the most unusual in appearance, and it would appear worth while to describe in some detail the observations of the activity obtained at the Flagstaff Station.

On October 2, 1961, P/Schwassmann-Wachmann 1 was recorded as a somewhat diffuse object of magnitude 18.5, nearly its normal brightness. On October 12, a 30-minute exposure revealed no trace of the comet to a cursory inspection. The comet at the time was near a stationary point, the total motion during the exposure amounting only to 2".5. Hence star images were not conspicuously elongated. The field of the comet was next observed on October 15. When the telescope was set, the comet was recognized visually at once, whereas it had not been recognized on October 12. The appearance was of a small, bright patch of nebulosity. Several exposures, of various durations, were obtained. The field, of course, overlapped with that of October 12 because of the slow motion. With the aid of the new plates the

## PLATE I



OCTOBER 12

OCTOBER 18

NOVEMBER 3

Official U.S. Navy Photograph

An outburst of Comet Schwassmann-Wachmann 1, 1925 II, in 1961. Each exposure was 30<sup>m</sup> on Kodak 103a-O with the 40-inch reflector of the U.S. Naval Observatory, Flagstaff Station. The reproductions have been carefully matched for density, scale, and orientation. The lines at the edges of the left panel indicate the position of the comet, which appears as the lower of two fairly bright stars. The diameter of the nebulosity was about 2'0 on November 3.

comet was recognized on the earlier plates as an apparently stellar object of 13th magnitude. Photographs on October 15 and on succeeding nights showed an expanding nebulosity of ring-tail shape, with the nuclear condensation embedded in one end of the nebula. The diameter of the nebula increased from 0'.4 on October 15 to 2'.5 by November 10, when it was becoming quite faint and ill-defined. The brightness of the nuclear condensation, on the other hand, decreased from magnitude 15.2 on October 15 to 18.8 by November 10. The changing appearance of the comet is shown in Plate I. Measured diameters of the expanding shell lead to a linear velocity of expansion of about 0.1 km/sec in this outburst, quite of the same order as the velocity of expansion measured in previous outbursts.<sup>8</sup>

Photoelectric or spectroscopic observations of P/Schwassmann-Wachmann 1 are difficult to obtain, except when the comet is bright. Furthermore, there is almost inevitably a delay of a day or two at the least between discovery of an outburst and the obtaining of photoelectric or spectroscopic observations. Spectrograms in the decay stages of outbursts have previously been obtained by Mayall<sup>12</sup> and by Herbig.<sup>13</sup> Photoelectric observations and an additional spectrogram were obtained by Walker and Mayall, respectively, following an outburst in December 1958. The results have been reported by Walker.<sup>10</sup> Observations suggest that the material of the expanding shell is dust which reflects the incident sunlight very slightly reddened.

It is important to point out that all spectroscopic observations thus far obtained record the comet well after the initial stages of an outburst. Most of the light in such observations came from the expanding dust cloud. It will be a real challenge to obtain observations while the comet is still in the stellar stage of an outburst.

Herget has recently published the results of a study of the orbit of Comet Schwassmann-Wachmann 1.<sup>14</sup> He finds that there are sometimes discontinuities amounting to as much as 20'' in the run of residuals from a generally very satisfactory orbit. The time resolution is not sufficient to permit a strong correlation of individual discontinuities with the more violent recorded outbursts. Furthermore, the possibility of displacements of the cen-

ter of light from the center of gravity because of asymmetry of an expanding shell needs investigation. But there is a strong possibility that nongravitational forces may exert a measurable effect upon the motion of this comet.

#### COMET TAILS

Though our understanding of the structure and development of comet tails is in a rather unsatisfactory state at the present time, a considerable body of observational evidence is accumulating. It may be safe to say that at sufficiently small distances from the sun all comets do, or would, develop tails. Though tails have generally been said to develop at heliocentric distances less than 1.5 a.u., many comets have been observed to have tails at considerably greater distances. At least one has had an impressive tail at a heliocentric distance of 5.0 a.u. Some comets have had two or more tails at the same time, including the most recently observed bright object, Comet Seki-Lines, 1962 *c*. In some tails, very intricate ray structure may be present, and great irregularities and rapid changes may occur in the flow of material from the head into the tail.

Tails exhibit a considerable variation in the degree of curvature, some being almost straight along the projected radius vector from the sun, and others being strongly curved and inclined at a considerable angle to the projected radius vector. When a comet has two tails, one is generally nearly straight, with detailed structure, and the other more strongly curved, nearly structureless, and appreciably inclined to the radius vector. The straighter tail is blue in color, readily photographed, but not so easily seen. Conversely, the more strongly curved tail is seen more readily, and is photographed most strongly in yellow light.

Near the head, where the tails are brightest, the curved and straight tails are seen nearly superposed. Therefore, photographs with small instruments that cover a large area of the sky reveal best the structure of the double tails.

Most spectroscopic observations of comet tails apparently refer to the area closest to the head, where the tails are seen superposed and the surface brightness is greatest, for spectrograms often fail to reveal a sorting of material in the different types of

tails. Nevertheless, considerable observational evidence supports the generally accepted view that the straight tails, which show the greatest structural detail and the most rapid changes, consist of ionized molecules. The more highly curved tails are composed of solid grains that simply reflect and scatter the incident sunlight. The existence of tails composed of neutral molecules appears open to doubt.<sup>15,16</sup>

Tails at heliocentric distances less than 1.5 a.u. may be of either the dust or the ionized-molecule variety. It has also been rather generally recognized that dust tails may be formed at very much greater distances, even as great as 5.0 a.u. There is presently under observation, however, a comet that has repeatedly been observed to have an active tail, displaying structure, at heliocentric distances decreasing from 5.0 a.u. at discovery to less than 3.0 a.u. The tail was proved to be blue at a heliocentric distance of about 3.0 a.u., when reasonable exposures with filters became possible. The fact that the tail is blue strongly suggests that it is composed of molecules that fluoresce in blue light and not of dust particles which reflect sunlight generally unaltered. More will be said about this comet later.

#### DUST TAILS AT LARGE HELIOCENTRIC DISTANCE

Several recently discovered comets of very large perihelion distance have had tails of distinctive appearance at great distances from the sun. The tails are featureless, apparently flowing from a clearly bounded envelope around the nuclear condensation. They are very nearly parallel-sided, the width of the tail remaining essentially the same as that of the head of the comet until the tail becomes too faint to detect at a distance of several minutes of arc from the head. Comets Baade, 1955 VI ( $q = 3.87$  a.u.), Haro-Chavira, 1956 I ( $q = 4.07$  a.u.), and Wirtanen, 1957 VI ( $q = 4.45$  a.u.) all had more or less featureless tails of this type at heliocentric distances of four or five a.u. The appearance of the tails of Comets Baade and Wirtanen is shown in Plates II and III. Note that Comet Baade also exhibited a fountain phenomenon in the region of the head, activity that continued for several months during the time that the tail was most readily visible. Material apparently was ejected from the nucleus into a

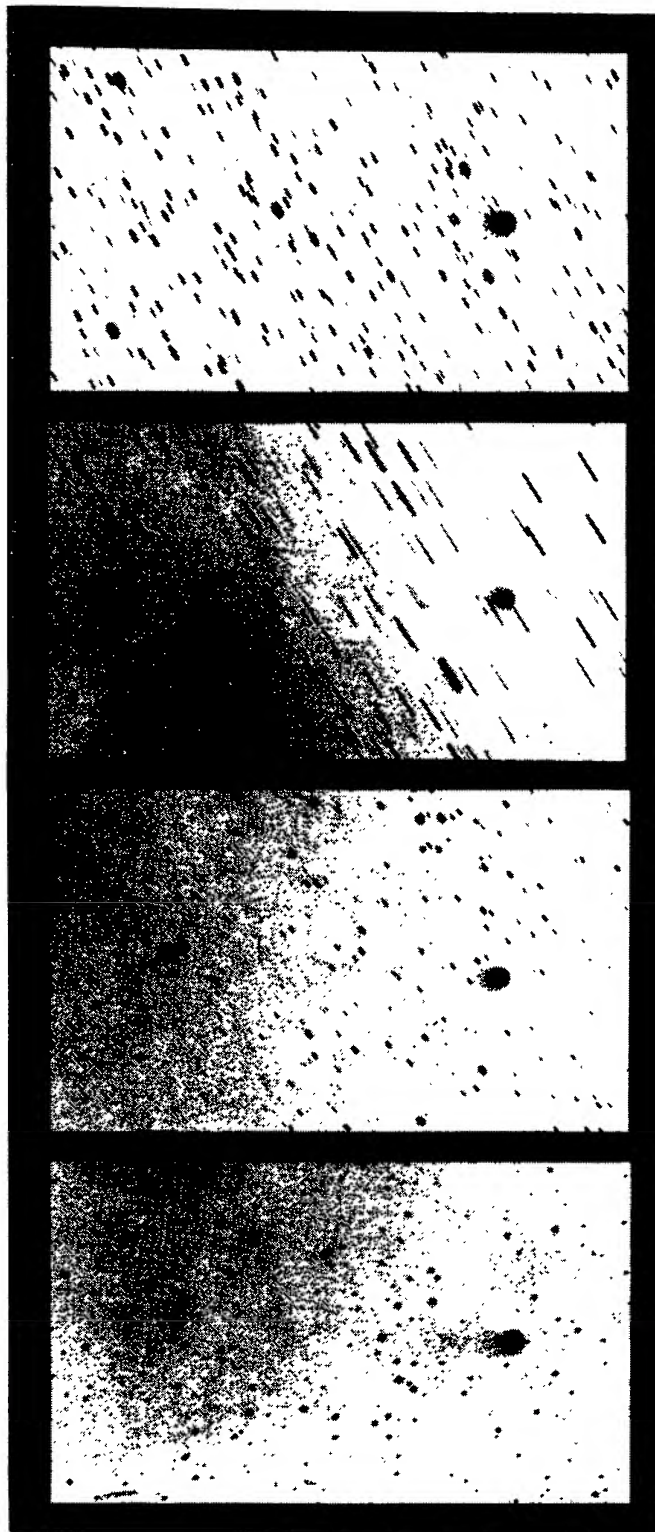
narrow sector of the coma; this material came under the influence of the radiation pressure from the sun, and was swept around into a sharply defined envelope and then back into the tail. Such a unidirectional emission of material was not evident with Comet Wirtanen, but the sharply bounded envelope around the nuclear condensation was just as conspicuous.

A study of the tails of Comets Baade and Haro-Chavira has been published by Osterbrock,<sup>17</sup> who found, on the basis of plates taken with the 48-inch Schmidt telescope, that the space position of the tails he studied was about midway between the radius vector from the sun and the tangent to the orbit behind the comet. The heliocentric distances were between 3.9 and 5.0 a.u. for his observations. Comments about cometary tails at heliocentric distances of 2.0 to 4.0 a.u. had previously been published by Beyer,<sup>2</sup> who found that the axis of the tail deviated increasingly from the direction of the solar radiation pressure, until, farther than 4.0 a.u. from the sun, the tail appeared to trail after the comet in the orbit.

Photoelectric and spectroscopic observations of Comet Baade were obtained by Walker in December 1955.<sup>18</sup> He found that the spectrum of the nucleus, as well as of the jet, was a pure solar-reflection type, without emission. The  $U, B, V$  measures corresponded to a main sequence star between G8 and K0, the light of the comet being slightly reddened relative to the sun. Walker remarked that the color index of the comet was very similar to those found for the bluer asteroids by Kuiper and his associates, but he hesitated to say what significance ought to be attached to this observation.

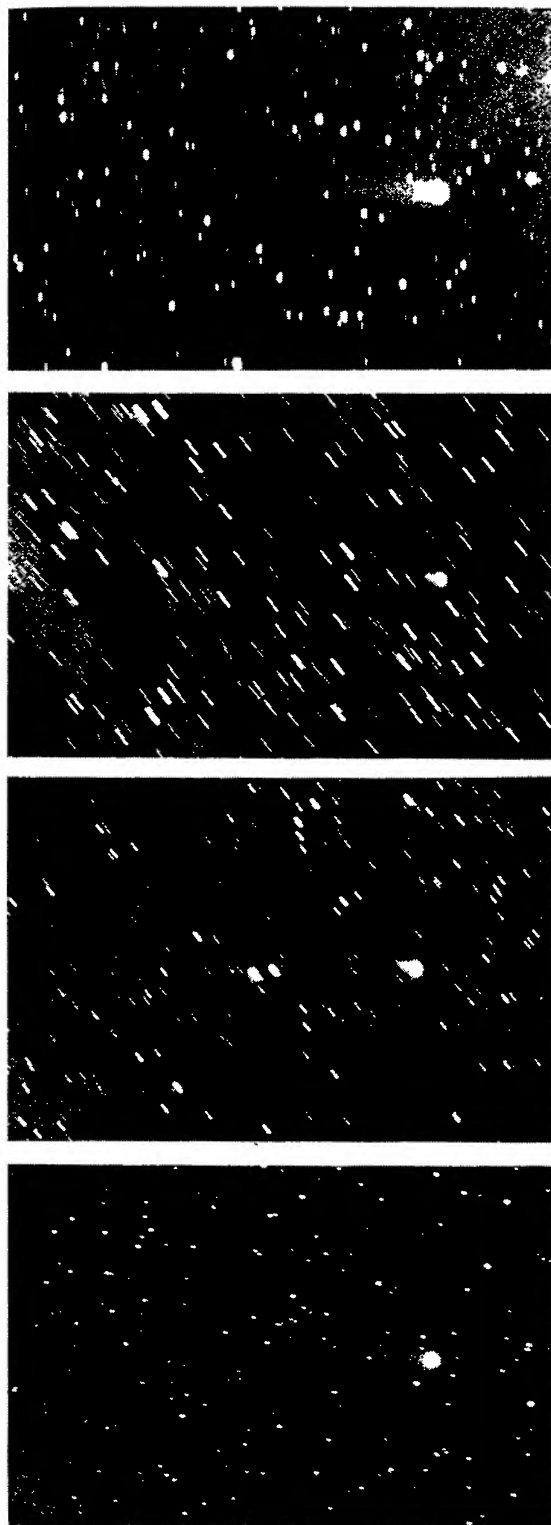
Though these comets apparently are giants, appreciably longer exposures are required to show the tails than are necessary for astrometric purposes. In the past it has been accepted that comets at large distance from the sun show no physical phenomena of interest. For this reason, and also because dark-of-the-moon time with the larger reflectors is scarce, few astronomers interested in comets have taken the long exposures required. From my own experience I suspect that tails of the type displayed by Comets Baade, Haro-Chavira, and Wirtanen are common. When a long-exposure photograph a few days after the discovery of Comet

PLATE II



Comet Baade, 1955 VI, showing the appearance of the head and tail in the autumn of 1955.

PLATE III



Official U.S. Navy Photographs

Comet Wirtanen, 1957 VI, showing the appearance of the head and tail in 1957 and 1958.

Humason, 1960 *e*, revealed a tail of the characteristic appearance, I even went so far as to predict (correctly) that this comet was far from the sun and moving in an orbit with large perihelion distance. But I hesitate to suggest that knowledge of comets has progressed to the point at which the general character of the orbit can be determined simply by studying the appearance of the object.

#### AN ION (?) TAIL AT LARGE HELIOCENTRIC DISTANCE

Comet Humason, 1961 *e*, was found by Milton Humason on September 1 last year with the 48-inch Schmidt telescope at Palomar. It was then an object of 14th magnitude, distant five astronomical units from the sun. As early as September 10 an impressive tail, considering the distance, was recorded on a photograph taken at the Observatoire de Haute Provence.

Beginning in October, a prominent and changing tail was recorded each dark of the moon on long-exposure blue plates at the U.S. Naval Observatory, Flagstaff Station, until the comet moved too close to the sun in February 1962 (see Plates IV and V). Since 60-minute exposures were required to record the blue-light appearance of the comet, the very much longer exposures that would be required in yellow light were impracticable. Late in May 1962, after conjunction with the sun, and when the heliocentric distance had decreased to 3.1 a.u., a tail was again recorded on blue plates at Flagstaff. But on May 31, for the first time at Flagstaff, the comet was recorded on blue and yellow exposures on the same night. The blue plate showed the usual (for Comet Humason) well-developed tail, but the yellow plate showed very little trace of even a coma. The conclusion seems almost inescapable: the light of the tail of Comet Humason is derived from strong blue emission.

The orbit of Comet Humason, as improved recently by B. G. Marsden from all available observations from discovery to conjunction,<sup>19</sup> is a long-period ellipse of perihelion distance 2.1 a.u. The period is somewhat under 3000 years, and the inclination is 153°. The comet was 2.2 a.u. above the plane of the earth's orbit at the time of discovery, but it passed through the plane in May 1962 and will be well south at the time of perihelion passage December 10, 1962.

Though it may be a vain hope to obtain spectra of the tail of Comet Humason, this object is being followed carefully by direct photography with suitable filters at several observatories, including the Flagstaff Station and the Palomar Observatory. The observations already available have awakened the interest of several astronomers in the behavior of this comet.

The position in space in which Comet Humason has been located is not unique in any obvious way, nor has there been long-continued solar activity that could explain the presence of the unusual tail in this particular comet. It would appear necessary to seek an explanation within the comet itself, perhaps in some unique characteristics of the material, or in some sort of ionizing or exciting process, or both, effective in the immediate vicinity of the nucleus.

It would seem most important to obtain observations of whatever character possible that could yield evidence of the nature of the radiation emitted from the tail of Comet Humason and of any unusual processes taking place in the head of this comet.

#### DISRUPTION OF THE NUCLEUS AT LARGE HELIOCENTRIC DISTANCE

Comet Wirtanen, 1957 VI, was an exceptionally interesting comet for several reasons. It was one of those comets of large perihelion distance described above, which for months had a tail of the type that seems to be more or less characteristic of great comets at large distance from the sun. It remained observable for four and a half years, and, when last observed at a heliocentric distance of 9.4 a.u. and a geocentric distance of 8.6 a.u., represented the second largest heliocentric distance to which a comet has ever been observed. (The record heliocentric distance was 11.5 a.u., for Comet Stearns, 1927 IV, when last observed in 1931.) Comet Wirtanen may prove to be most interesting for another reason not yet mentioned.

Comet Wirtanen was discovered on March 16, 1956, by C. A. Wirtanen with the 20-inch Carnegie astrograph of the Lick Observatory. It was then a condensed object of 15th or 16th magnitude, with a short, faint tail, and was almost 5 a.u. from the sun. The new comet was followed regularly at several observatories

PLATE IV



Official U.S. Navy Photograph

Comet Humason, 1961 *e*, on October 4, 1961. The exposure was 60<sup>m</sup> on Kodak 103a-O. The heliocentric distance of the comet was 5.0 a.u., and the geocentric distance 4.1 a.u.

PLATE V



Nov. 12, 1961

Dec. 2, 1961

Dec. 26, 1961

Official U.S. Navy Photographs

Comet Humason, 1961 *e*, late in 1961. Each exposure was 60<sup>m</sup> on Kodak 103a-O ; all are reproduced on the same scale.

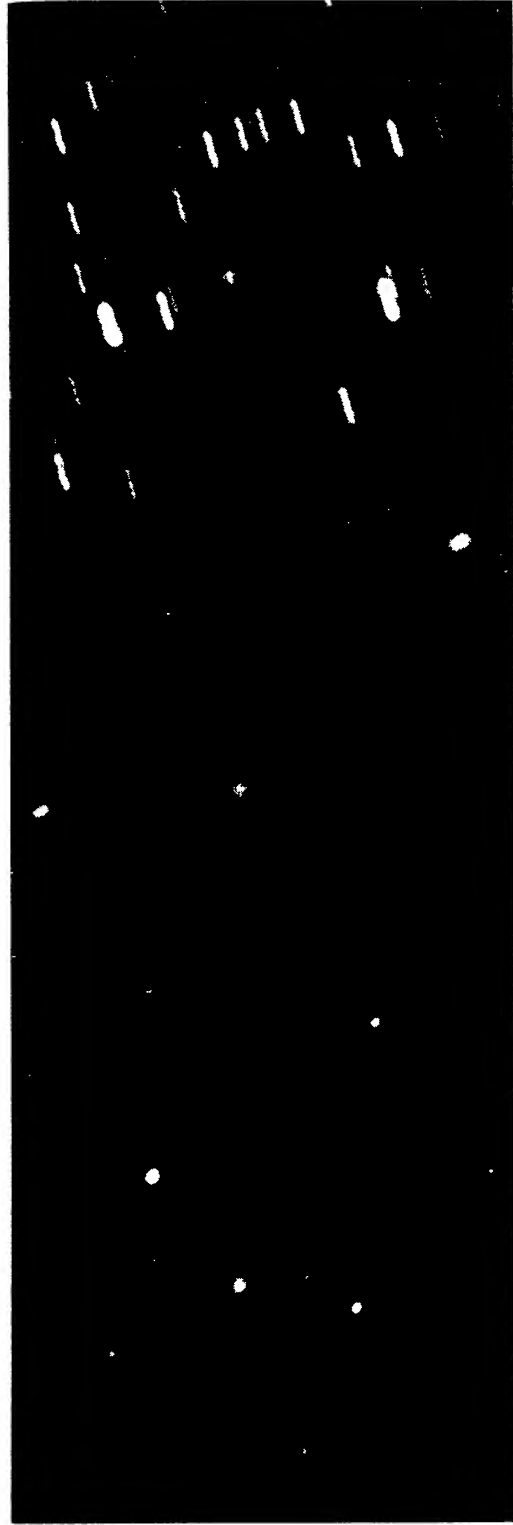
## PLATE VI



Official U.S. Navy Photographs

Comet Humason, 1961 *e*, on May 31, 1962. The left panel shows a 20<sup>m</sup> exposure in blue light while the right panel shows an exposure of 39<sup>m</sup> in yellow light. The star field appears similarly exposed on the two plates. The heliocentric distance was 3.0 a.u. and the geocentric distance was 3.3 a.u.

## PLATE VII



Official U.S. Navy Photographs

Comet Wirtanen, 1957 VI, showing the increasing separation of the two nuclei. All three exposures are reproduced to the same scale. The dates of the exposures, geocentric, and heliocentric distances are (l. to r.): July 21, 1957  $\Delta = 4.0$ ,  $r = 4.5$ ; April 11, 1958,  $\Delta = 4.6$ ,  $r = 4.8$ ; July 11, 1959,  $\Delta = 6.2$ ,  $r = 6.9$  (all in a.u.).

until early June 1956, when it was approaching conjunction with the sun.

Following conjunction, on May 1, 1957, the nucleus was found by G. Van Biesbroeck to be double, the two components separated by some 8'' and differing by three magnitudes in brightness. The two nuclei were observed for more than two years by Van Biesbroeck, by H. M. Jeffers and his assistants, and by E. Roemer. The angular separation gradually increased, amounting to some 20'' during the 1958 observing season, and not quite 30'' in 1959. The difference in magnitude decreased steadily, amounting to only about one magnitude in 1959. Sample photographs of the changing appearance of the comet are reproduced in Plate VII. The last plates, a pair of 120-minute exposures made at Flagstaff in September 1960, recorded the comet as a very faint image near the plate limit. Only one condensation was present, the secondary nucleus apparently being below the limit.

The increase in the observed angular separation corresponds to a steady, unaccelerated increase in the component of the linear separation projected on the sky. The values of the separation calculated from the measures of the three principal observers are very consistent, and it is possible to deduce with only a small uncertainty the time of disruption of the nucleus and the component projected on the sky of the velocity of separation.

The disruption of the nucleus took place at the beginning of January 1957, with an uncertainty of only a few days. The comet was then not quite 4.9 a.u. from the sun and about 2.0 a.u. south of the plane of the earth's orbit. The apparent angular separation of the nuclei when last observed in July 1959 corresponds to a linear separation of a little less than 130,000 km. The minimum velocity of separation, observed to be constant, is then 1.6 meters/sec.

Though the space velocity of separation of the two nuclei obviously must be greater than the escape velocity, the component projected on the plane of the sky may not alone exceed this limit. We have, however, no information on the velocity of separation of the nuclei in the line of sight, and therefore cannot derive the space velocity of separation. The assumption that 1.6 meters/sec is equal to the velocity of escape may not be a gross deviation from

the truth and at least gives us a way of estimating the mass of this comet from dynamical information. An assumption as to the distance between the center of mass and the point of separation also is necessary, and 10 km almost certainly is not wrong by more than an order of magnitude. With these assumptions, the mass of Comet Wirtanen is found to be of the order of  $10^{17}$  gm, a value within the range of cometary masses calculated by other methods. The character of the information and assumptions that have been used in deriving this value of the mass is such that  $10^{17}$  gm probably represents a rather conservative estimate; the actual mass may be appreciably greater. Furthermore, there can be no doubt whatever that Comet Wirtanen is an exceptionally large comet.

It is also of much interest to consider what type of event could cause a fracture of the nucleus of a large comet at great distance from the sun. A collision, or an internal explosion of some sort seem the most likely possibilities. Tidal disruption appears to be ruled out by lack of a close approach to a sufficiently massive body.

At the time of the disruption, Comet Wirtanen was not within the volume of space occupied by ordinary minor planets. But the location, at a distance just slightly less than that of Jupiter, below the plane of Jupiter's orbit, and at a longitude some  $45^\circ$  east of Jupiter, was well within the libration limits of the Greek Camp of Trojan Asteroids. The velocity of the comet in its orbit would exceed the mean velocity of a Trojan by some 5 km/sec. Since the perihelion distance of Comet Wirtanen was 4.45 a.u., the radial component of the comet's velocity would not be large. The relative velocity, in case of an impact with a Trojan, would then be a few km/sec. Since we know little of the physical properties of a comet nucleus, it would be highly speculative to suggest possible results of such a collision.

Observations of outbursts of P/Schwassmann-Wachmann 1 demonstrate that energetic processes are possible within the nucleus of a comet even at very great distance from the sun. Nevertheless, these outbursts appear to be essentially a superficial phenomenon, the obvious signs of an outburst disappearing completely within a few weeks at the most. The situation with Comet

Wirtanen is fundamentally different in that a substantial chunk was suddenly separated from the nucleus to pursue an independent, long-lived existence in space. Almost certainly the rupture extended to considerable depth in the nuclear body. So little is known of such events that it is difficult to suggest a mechanism.

It has been my aim in describing events that occur in comets at great distance from the sun to call attention to phenomena about which little is known and almost nothing has been published. The observational effort expended on these remote comets has been quite modest thus far, and it seems likely that greater endeavors would reap rich returns in terms of understanding of comets and the solar system in general. I hope that this review will serve to increase awareness and stimulate interest.

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<sup>1</sup> P. Swings and L. Haser, *Atlas of Representative Cometary Spectra* (Liège Institut d'Astrophysique, 1956), p. 19.

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