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EVOLUTION OF A SPIRAL JET IN THE INNER COMA OF COMET HALE-BOPP (1995 O1)

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ABSTRACT

We present observations of the evolution of a prominent spiral jet in the inner coma of comet Hale-Bopp (1995 O1). The observations, taken with the 82 cm IAC-80 telescope at the Teide Observatory, were made on 1995 August 25, 27, 28, and 31, and on September 4–7, as part of an ongoing program of monitoring the comet in Tenerife. The jet is observed to show a nearly, but not completely, constant position angle over the two weeks of observation. Although it is generally assumed that the jet is a dust event, some aspects of the morphology and behavior mean that the hypothesis that it is a gas jet cannot be ruled out. No single hypothesis is thought to be completely satisfactory. Between our first detection of the jet on August 25 and its disappearance on September 7, we see the point of inflection within the jet expand away from the nucleus at a highly constant velocity. At the same time, the jet fades considerably. This jet event seems different from others that have been observed later because the collimation of the beam is very tight, rather than the highly wound spiral structure shown by some later jets.
Subject headings: comets: individual (Hale-Bopp 1995 O1)

1. INTRODUCTION

Comet Hale-Bopp was discovered visually by A. Hale and T. Bopp (Hale & Bopp 1995) on 1995 July 23 at the unprecedented distance of 7.3 AU from the Sun, by far the greatest distance for a visual comet discovery, and unusual even for photographic or CCD discoveries. Since the comet exhibits a very bright total visual magnitude at discovery, it is evident that it is either particularly large and/or active or is suffering an exceptional outburst. Despite the announcement of various prediscovery images of the comet, the very sparse coverage that they offer and the doubts expressed about some of these images mean that it is still not obvious whether comet Hale-Bopp is a giant object showing its "normal" activity or a rather smaller object showing an outburst. As a consequence, there is a range of at least 10 mag between the best and the worst cases in the extrapolation of its light curve to perihelion (Kidger 1995). One way of distinguishing between scenarios is to establish the comet's degree and pattern of activity. A high and stable degree of observed activity, combined with a consistently bright total magnitude, would indicate that the more optimistic predictions about the light-curve evolution may be correct. In contrast, single-vent activity (from a lone active zone) would be a warning sign that the comet may not fulfill the more optimistic predictions, even fading out before perihelion.

Indirect evidence, such as the multiple similarities to comet 1811 I (the orbit, very bright absolute magnitude, and activity at high heliocentric distance), has been used (Marsden 1995) to suggest that comet Hale-Bopp may be similarly spectacular near perihelion, although there is little strong physical evidence that exists to support either of the extreme scenarios (very bright or fizzle). Jet activity at high heliocentric distance, though, is potentially a good indicator of the intrinsic activity of the comet. No really bright object has been observed since comet West in 1976, hence, the apparition of a potentially magnitude zero (or brighter) comet, which will be well positioned to observe from the northern hemisphere for several months around perihelion, is of great interest for cometary physics. The fact that the comet is still 18 months from perihelion allows detailed observing plans to be made. The advances in astronomical instrumentation since 1986 will allow detailed spectroscopic and morphological studies to be made that have never previously been possible, especially if the comet is particularly bright.

Reports were made soon after the discovery of unusual activity (Offut 1995) with a spiral coma developing and decaying. This has been interpreted as outburst activity similar to comet P/Schwassmann-Wachmann 1 (Sekanina 1995a). Such activity allows, in principle, the rotation period of the nucleus to be estimated from the change in position angle of the jet (for gaseous events), or from the synchrone trajectory (for dusty events). To date, very few comets have a really well-determined rotation curve, and, even in the case of P/Halley (the best observed object), the presence of both 50 hr and 7 day periods means that there is no real consensus as to the exact mode of rotation and precession around the long and short axes of the nucleus.

2. OBSERVATIONS

Regular observations of comet Hale-Bopp were started on August 10 using the CCD camera of the 82 cm IAC-80 telescope sited in Instituto de Astrofísica de Canarias's Teide Observatory, Tenerife, Canary Islands, Spain. A Thomson 1024×1024 chip was used, offering a field of nearly $7\farcm5$. Standard *BVRI* broadband filters were used.

Because of the movement of the comet and the inability of the telescope at present to track differentially, comparatively short exposures are taken (each of 300–400 s), which are then recentered on the cometary nucleus and summed to give any desired total exposure. The position of the nuclear condensation was measured using the *imexamine* routine, and images were combined using the *imcombine* routine, both included in

TABLE 1

OBSERVING LOG FOR THE OBSERVATIONS OF THE JET

UT Date	Band	Number of Images	UT Range	Total Exposure (s)	Notes
Aug 15	*R*	6	22:33–23:12	2400	
Aug 25	*R*	21	21:19–23:47	7400	
Aug 27	*R*	6	20:35–22:33	1620	Cirrus
Aug 28	*B*	23	21:06–23:21	6800	Cirrus
Aug 31	*R*	15	20:12–21:45	4500	Cirrus
Sep 4	*R*	42	20:51–23:00	5040	
Sep 5	*R*	23	20:35–22:49	6900	Cirrus
Sep 6	*R*	24	20:24–22:50	7200	
Sep 7	*R*	14	21:23–22:42	7200	
Sep 8	*R*	23	20:31–22:44	6900	

the Image Reduction and Analysis Facility (IRAF)[1] environment. Images were previously flat fielded using very high S/N master dome flat fields obtained by combining many individual exposures.

On some nights exposures were taken in all four filters to give color information, but, on the eight nights to be discussed here, many exposures were taken in a single filter, with the aim of combining them into a very deep image in a single band. On discovering the jet, our observing program switched to intensive monitoring in a single band on each night, to follow the jet evolution with time. The observing log for the eight nights in question is given in Table 1.

3. RESULTS

On-line visual inspection of the images from August 28 revealed an unusual jet emanating from the nucleus in P.A. = 280°. This jet wrapped around the nucleus to P.A. = 030° approximately. The jet was also detected by Jewitt & Chen (1995) some 9 hr after the start of observations from Teide Observatory. On inspection of images from previous nights, the jet was found to be very obviously present when the images were scaled logarithmically to show the central condensation, rather than being scaled to show the extended coma.

On August 25, the jet was significantly less extended in position angle than on August 28, being clearly detected only to P.A. = 000° approximately. The observations on August 27 were taken through an occasionally dense cirrus cloud, which much reduced their quality. Even so, the jet can be clearly traced from the nuclear condensation to P.A. = 020° approximately, rather less than the observed extension on August 28, but consistent with the poorer conditions.

To investigate the possible rotation of the jet, the images from each night were grouped to give high S/N master frames. The images from August 25 and 28 were split initially into three sets of seven or eight frames, recentered and combined. All the usable images from August 27 were combined into a single frame. This frame was first smoothed slightly with a low-pass Gaussian filter, and then a Laplacian filter was applied, leaving just the jet and inner part of the central condensation visible. The combined and recentered frames were then converted to MPEG format and animated (not shown here, but available at http://www.ll.iac.es/general/index.html) to show the evolution of the jet visually and dynamically. For the purposes of this paper, though, all images from a single night have been combined, given that we can rule out the existence of a significant rotation within a single observing run. Figures 1(*a*)–1(*e*) (Plates L21–L25) show the final reduced images for the nights when the jet is most clearly seen. From September 4, the visibility was greatly reduced, partly by the reduction in surface brightness and partly by the proximity of the Moon. The jet is seen to have a three-part structure: there is an initial narrow straight jet of material ~7″ long and gradually increasing with date, leaving the nucleus in P.A. ~ 280°. This straight section appears to be highly collimated and has negligible curvature. This we refer to as "the collimated jet." This section abruptly changes direction by 90° and opens out at a comparatively narrow opening angle before starting to sweep round to the east and opening out further. Similar behavior was reported by West (1995), who also observed the jet on several nights, confirming the position angle of the collimated jet and its constancy.

Considerable differences are seen in the structure of the jet between August 25 and 31. Apart from the extent of the jet in position angle, it is seen to be wider and much brighter on the former date. The initial collimated section of the jet increases slowly in length as it fades. We cannot rule out, though, that there is a small oscillation in position angle, although this appears to be less than ~15° and of indefinite period. There is, though, no significant rotation of the jet on timescales of either a few hours or a few days. We also note that the position angle given by Jewitt & Chen (1995), observing from 7–9 hr after us on August 26, was also 280°.

The end of the jet increases its distance considerably from the nucleus, giving the false impression of rotation because it is "unwinding." On August 31 and September 4, the trend of a gradual fade and pronounced increase in distance of the "spiral arm" from the nucleus continues. After September 4, precise measurements of the jet are extremely difficult due to its faintness. On various nights, the data taken were nonphotometric or of dubious photometric quality. This makes it difficult for us to quantify the rate of fade of the jet, a potentially powerful diagnostic tool of its composition.

We are unable to say exactly when the jet appeared. There is no sign of it in the images from August 15, which we include for comparison to show that there are no important artifacts created by our reduction procedure. From the rate of growth of the jet, we estimate that it took several days before our first detection. Various reports on the Internet from reliable visual observers speak of a sharp brightening of the nuclear condensation of the comet around August 20, consistent with the initiation of an outburst. Figure 2 shows the growth of the linear section of the jet during the observations. A highly linear expansion is seen, with a projected velocity of 32 m s^{-1}, which cuts the *x*-axis at −7.69 days (August 17.31); although there is no strong reason why this should be the actual date of initiation of the structure.

4. DISCUSSION

The most popular explanation presented to date is that the jet is a pure dust event, caused probably by CO sublimation, and that the curvature reflects synchrone trajectories of grains of very different sizes. If the jet is caused primarily by dust (or ice) and neutral gas ejection, no rotation in position angle would be seen, although the morphology of the jet would

[1] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under cooperative agreement with the National Science Foundation.

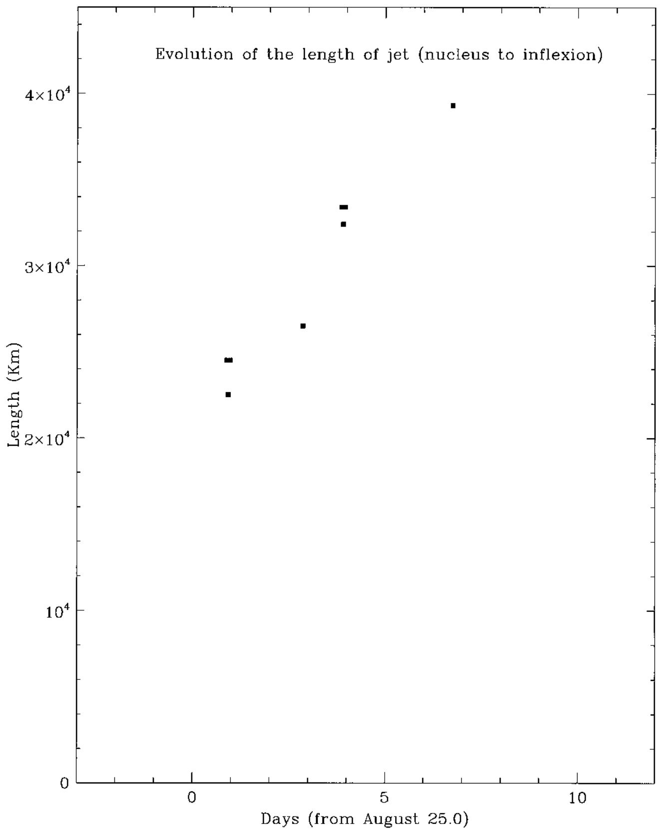

FIG. 2.—Evolution of the length of the jet from the nucleus to the point of inflection over the period covered by these observations. A steady increase in length can be seen.

reveal the rotation period and axial inclination. This explanation is favored by various authors (e.g., Sekanina 1995b, c).

To obtain a good fit to the jet morphology, some very tight constraints are made on models. It is necessary to suppose that the event was caused by the combination of synchronized venting or two independent orifices. A small time delay between the initiation of venting from the first and the second orifice, combined with perspective effects, can reproduce both the highly collimated beam and the spiral structure at the end of it. In this model, one orifice causes the collimated beam and the second the spiral structure. Support for a dust model is given by the fact that the velocity of expansion is very much lower than the gas velocity for CO expulsion (~30 m s^{-1} against ~1000 m s^{-1}), although the true velocity may be significantly higher if we are looking along the jet.

Given the observed timescale of jet events (approximately one per month), it is statistically implausible that two independent venting episodes would be triggered nearly simultaneously. The fact that a later jet has produced a somewhat similar morphology with a position angle close to 000° makes us reluctant to accept this model at present, despite its obvious attractions. A further problem that has yet to be fully addressed is whether the venting is a single instantaneous event (see below) or a continuous emission over a number of days; significant difficulties with the fit are found if a long duration of emission is assumed. A long-duration event, though, is more in accord with the thermal triggering mechanism and long rotation period that have been proposed to explain the venting (Sekanina 1995d).

An alternative method (Shulman 1995, private communication) proposes to explain the jet in terms of an invisible gas beam carrying visible dust within it. The jet is seen as a two-dimensional projection of an Archimedes spiral. This method does not require synchrone trajectories, thus removing one potential difficulty, although it is similar in some respects to the model proposed by Sekanina. An important difference is that this model assumes a single emission event of very short duration, thus avoiding some of the morphological difficulties. No specific triggering mechanism is assumed, although thermal triggering is felt to be unlikely. The model is proving to be promising in its results and, contrary to the synchrone model, suggests that the different jets originate from different points on the nucleus. However, it requires further development, given that some aspects of the jets' development are still problematic at present, particularly the derived ages of different parts of the jet.

We have been struck by the peculiar morphology of the August jet event, some aspects of which appear more consistent with a plasma event than with pure dust emission. The jet shows a very narrow, highly collimated section that expands away from the nucleus. This shows a 90° break at a projected distance initially of 23,000 km, at which point the material directs itself very precisely in the antisolar direction. This could be due to a chance alignment, and it is also consistent with a plasma-jet model. The ejected material proceeds outward until it reaches the contact surface and is open to the influence of the solar wind. At this point, solar wind pickup occurs and the position angle is abruptly changed as it sweeps round the contact surface until it reaches a position angle corresponding to the antisolar direction. The fact that the end of the jet was very closely aligned with the antisolar direction[2] favors a plasma model.

Our data limit any possible position angle change in the jet to a maximum of ~15°, which implies that, if the jet is caused by plasma, it is located close to, but not at, the pole of the nucleus. This is consistent with the slight jitter that is seen in the position angle between the grouped integrations. This jitter is less easy to explain given a dust-jet model.

We find that the point of inflection, where the jet suddenly comes under the influence of the solar wind, is at a projected distance ~23,000–39,000 km from the nucleus, according to the date of observation. This gives us an estimate of the projected distance of the contact surface, where a local equilibrium exists between the pressure of the solar wind and the gas pressure within the inner coma. The angular distance of the point of inflection from the nucleus is seen to increase with time. This is not a perspective effect, since the geocentric distance was increasing slowly during the observations, but rather reflects what would be a genuine increase in the radius of the contact surface (Table 2). This we can understand if there was a significant increase in gas production corresponding to the jet event, and if the contact surface expands until reaching a new pressure equilibrium.

Figure 2 shows the variation of the linear extent of the collimated jet with time. Note that these are projected distances, and that the true distances, and hence the derived velocity of expansion, may be much greater if the viewing angle of the jet is not close to 90°. To make the plasma jet model

[2] Something similar is observed with the September jet-event and probably with the October event, suggesting that this is not simply coincidence, given the rather different morphologies, position angles, and evolution that have been seen.

TABLE 2

DETAILS OF THE OBSERVATIONS OF THE JET[a]

Date	UT Time	Angular Extent	Linear Extent (km)
Aug 25	21:19	5″.4	24,500
Aug 25	22:13	5″.0	22,500
Aug 25	23:11	5″.4	24,500
Aug 27	20:34	5″.8	26,500
Aug 28	20:56	7″.3	33,400
Aug 28	21:48	7″.1	32,400
Aug 28	22:44	7″.3	33,400
Aug 31	21:01	8″.6	39,300
Sep 4	21:56	11″.2	51,400

[a]NOTE.—The angular and linear extent refer to the distance between the nucleus and the point of inflection where the jet is swept back by the solar wind.

more plausible, we have to suppose that there is a significant projection effect and that the length of the collimated jet is actually significantly greater than 23,000 km; this would permit a significant fraction of the molecules *in the jet* to become ionized, even if the density of ions in the inner coma as a whole is rather low.

An obvious difficulty with this model is the lack of visible ions in the spectrum. The most likely species to be detected at high heliocentric distance, because of its abundance and very strong lines, is CO^+. Observations in the submillimetric range have shown significant neutral CO emission, with a production rate when no jet was active of ~1 tonne s^{-1} (Matthews, Jewitt, & Senay 1995; Rauer et al. 1995), but no reports have been made of the presence of CO^+ lines in the spectrum. Other species, though, may exist that do not have easily detectable lines. *IUE* observations have established an upper limit to H_2O production, although this corresponds to 3 tonnes s^{-1}. Since H_2O is a high-temperature volatile, it is unlikely to be more active than CO anyway. An alternative low-temperature volatile is NH_3; the NH_2^+ line is a well-known line in cometary spectra but is very weak and difficult to detect, except in very high S/N spectra.

Assuming that the jet is well described by a gaseous emission, which is later photoionized, and that the emission is slow enough to permit the coma to be in a quasi–steady state, the distance between the nucleus and the point of inflection can, in theory, be used to make an estimate of the total gas production rate. This assumes a model suggested by Schmidt & Wegmann (1982). Various difficulties are found that obviate the possibility of obtaining a firm numerical estimate, in particular, the fact that only the *projected* distance of the point of inflection is known.

This very simple model would give a rather high total production rate compared with the measured production rate of CO or the upper limit to H_2O. Since the CO production rate was measured with a quiescent nucleus, it is not impossible that at the peak of outburst the production rate could be 2 orders of magnitude higher than this quiescent level (~100 tonnes s^{-1}). The observation of large variations in the total brightness of the comet and morphological changes reported by visual and CCD observers (e.g., formation of an intense starlike nucleus) lends support to the idea of a highly variable production rate.

None of the three models that have been proposed are at this juncture wholely satisfactory, and further work is needed on all of them. This means that the plasma-jet model cannot be rejected simply because there is a proved alternative explanation that renders it unnecessary.

5. CONCLUSIONS

This paper presents a small subset of our data that covers 46 nights of imaging to the last week of October. Work is progressing on detailed modeling of the observations taken so far, including photometric calibration and, where available, color information. A more detailed report on our monitoring is being prepared (Kidger et al. 1996). We hope that further analysis will allow us to differentiate more exactly between models.

We find that the jet observed in comet Hale-Bopp (1995 O1) between 1995 August 25 and September 7 shows a highly characteristic morphology and evolution. Some aspects of this morphology and evolution are challenging to dust-ejection models and may be more consistent with a plasma model. No single model, though, is totally satisfactory, and we hope that the observations reported here will open a debate on the various possible models and their limitations. We stress that the observed morphology, distances, and velocities reported are *projected* values only and may bear no relation to the true situation. Observations of the comet are continuing, and a detailed examination of the different events observed to date may shed more light on their causes and the validity of the different models.

The authors would like to thank the telescope operators at Teide Observatory (Luis Chinarro, Angel Gómez, Luis Manadé, and Santiago López) for their work in taking images of the comet during the extended monitoring campaign, and Jesús Jiménez for making the telescope readily available to us.

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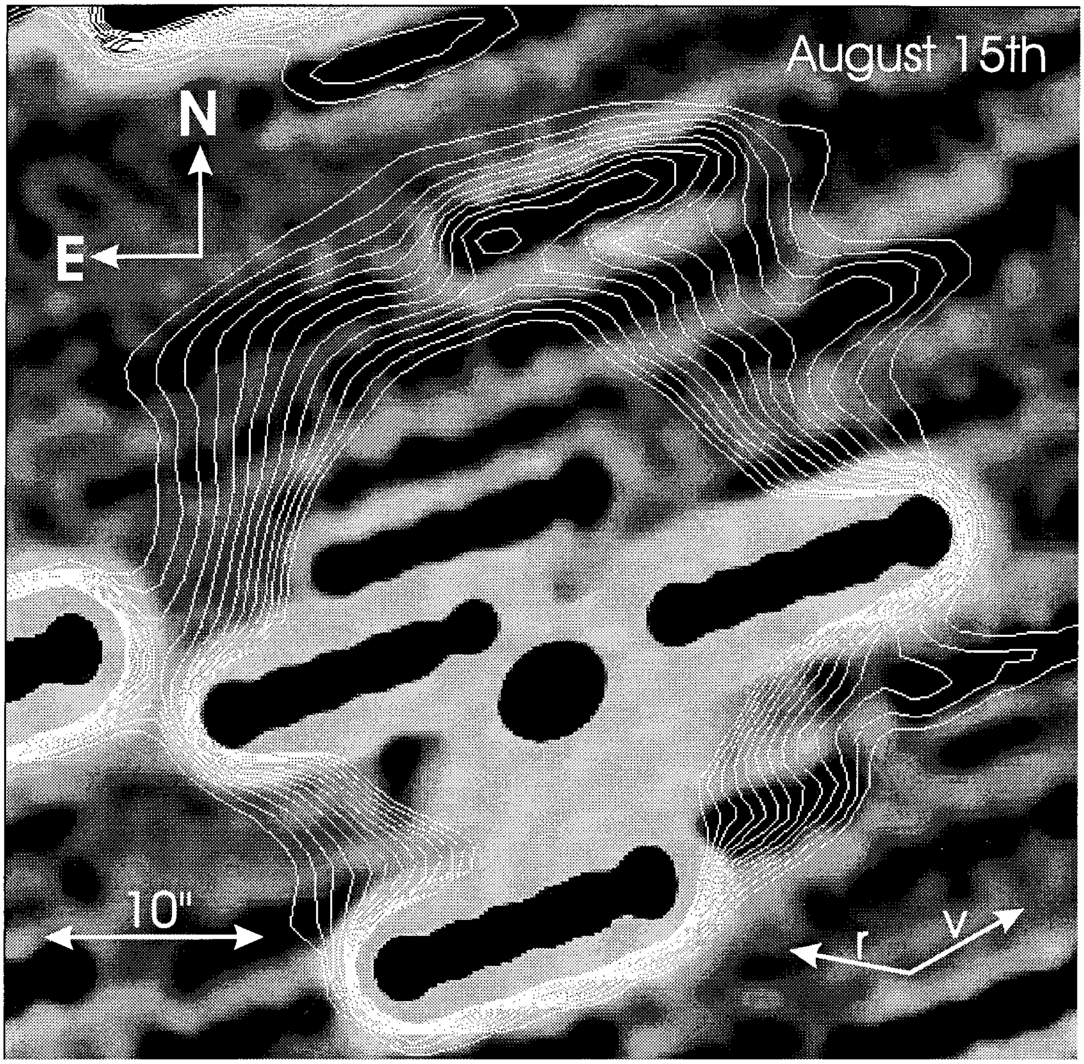

FIG. 1*a*

FIG. 1.—Processed images of the near-nucleus region of comet Hale-Bopp (1995 O1) from (*a*) August 15, (*b*) August 25, (*c*) August 27, (*d*) August 28, and (*e*) August 31. Contours of the coma brightness have been drawn only at distances well beyond the jet, to show that the outer coma was very nearly circular at this time, despite the near-nucleus activity. Contours are drawn at intervals from 1 σ to 5 σ of the sky brightness. The direction of the projected cometary velocity vector (***v***) and the antisolar direction (***r***) are marked, along with the scale and orientation of the figures.

KIDGER et al. (see 461, L120)

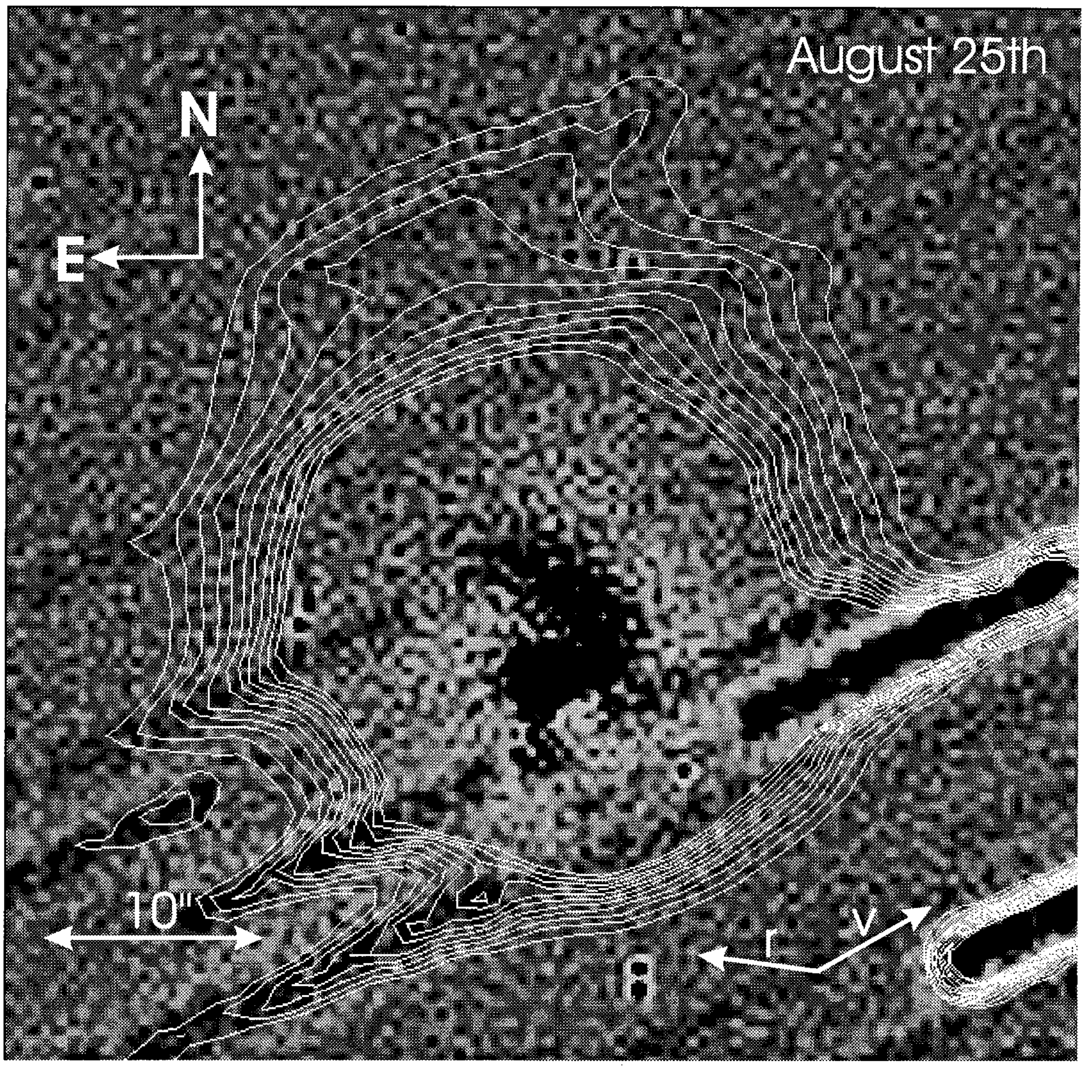

FIG. 1b

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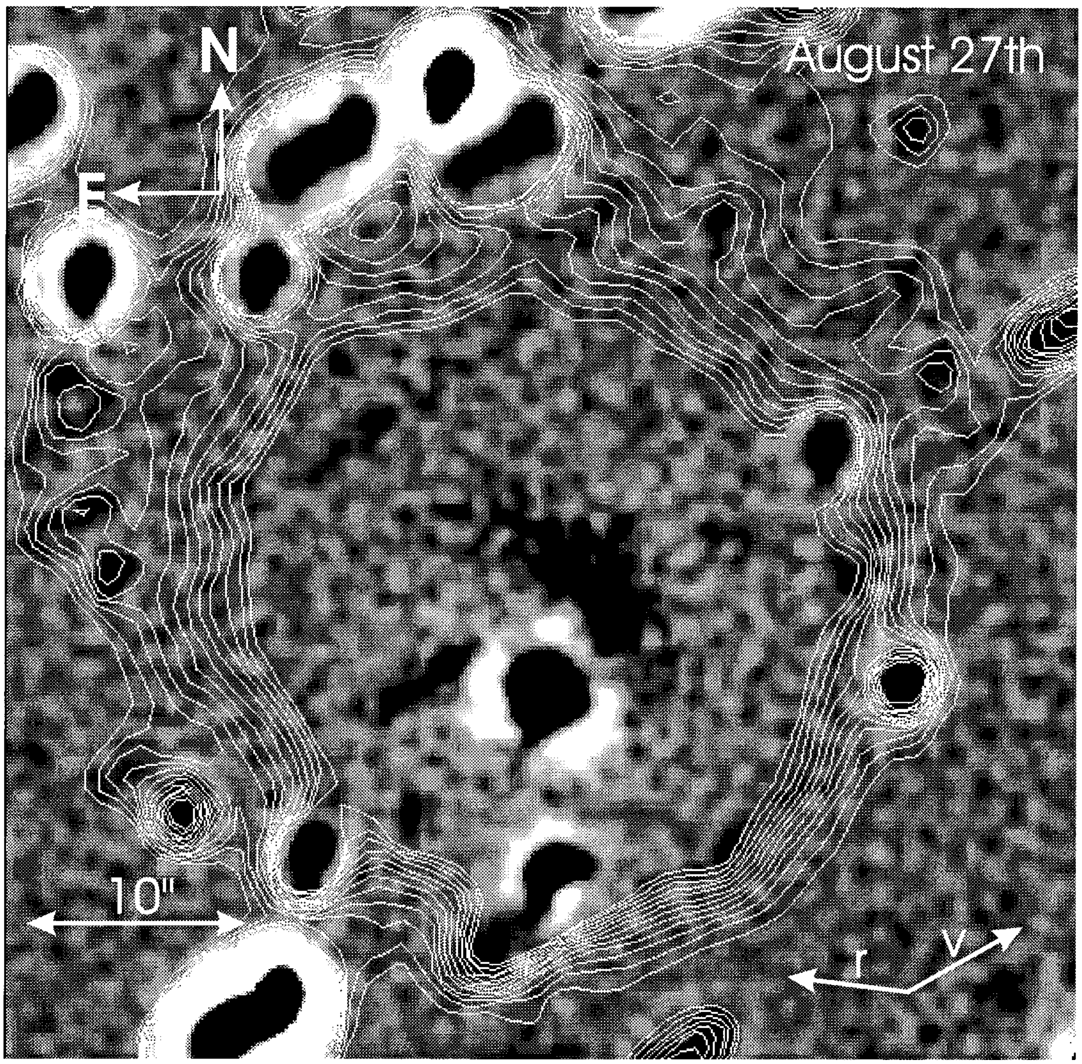

FIG. 1*c*

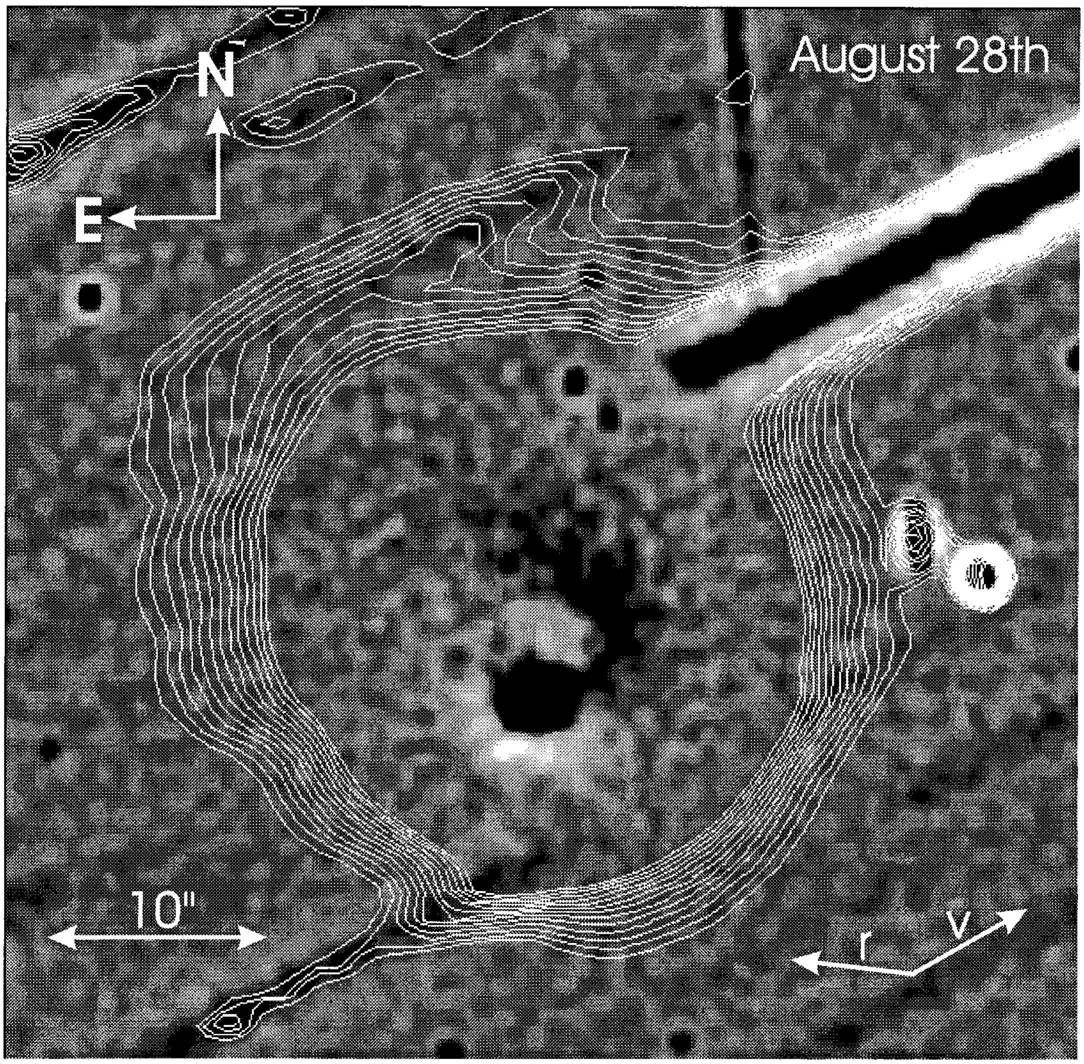

FIG. 1*d*

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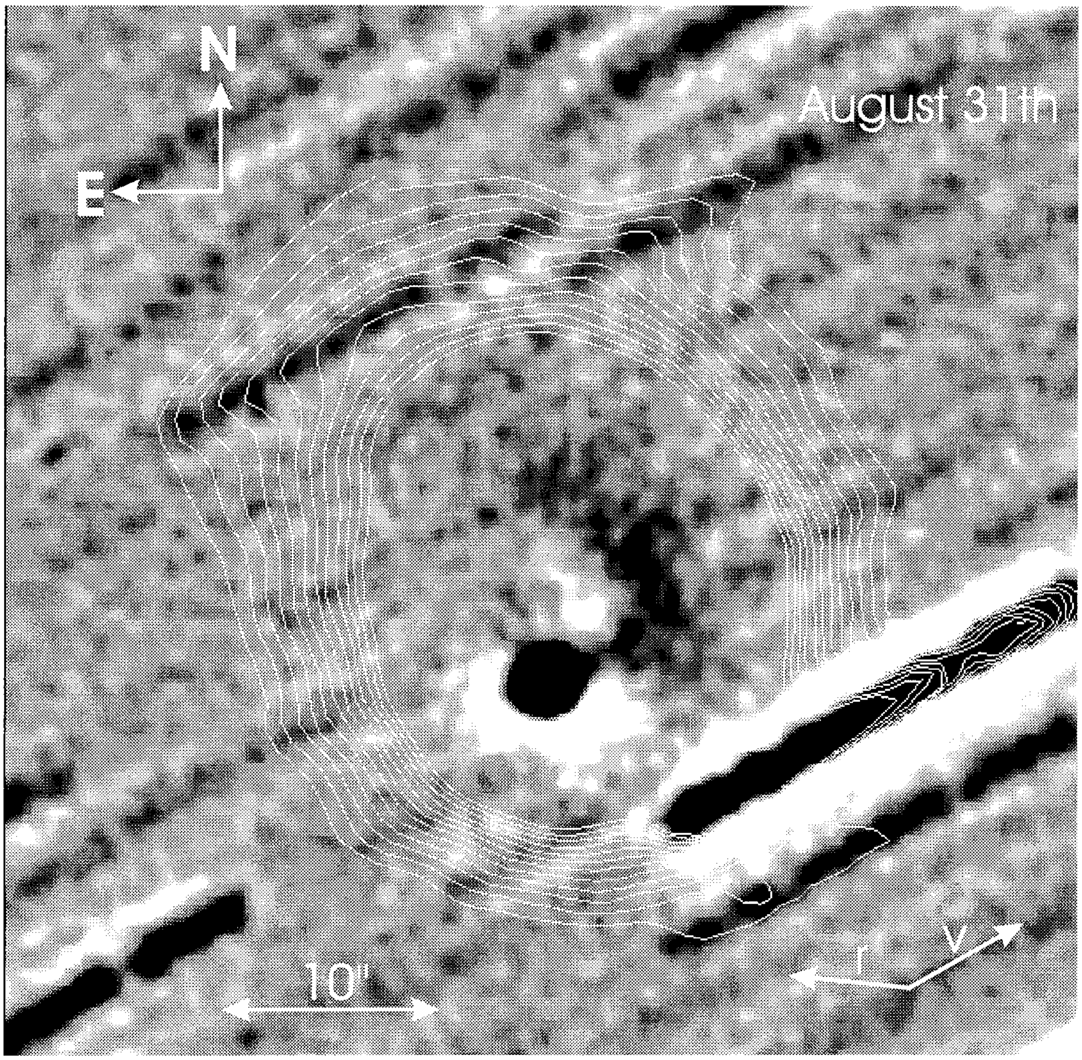

FIG. 1*e*

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