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DISCOVERY OF OUTFLOWS FROM YOUNG STELLAR OBJECTS IN BOK GLOBULES

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ABSTRACT

We present the results of a successful search for outflows associated with low-mass young stellar objects (YSOs) in a sample of 41 small Bok globules. This search was performed in the ^{12}CO $J = 1$–0 spectral line using the new multibeam receiver (QUARRY) of the Five College Radio Astronomy Observatory. We found new outflows in about one-third of the sample (14 of 41). In addition, we found five globules to be rotating, with velocity gradients in the range 0.1–0.7 km s^{-1} arcmin^{-1}. The presence of an outflow was found to be correlated with the value of the *IRAS*-based spectral index (between 12 and 25 μm) of the YSOs. Outflows were not detected in most globules whose *IRAS* point sources had spectral indices consistent with T Tauri or older stars. We infer that outflows occur during a fairly early stage of the star formation process when the YSOs are still deeply embedded in gas and dust. Globule YSOs with outflows have gas velocity dispersions significantly larger than globules without outflows. Thus, the good mechanical coupling observed to exist between the outflow and the ambient cloud seems to support the idea that outflows can be responsible for a variety of effects, including cloud support, dispersal, or the end of accretion onto the forming star. Both the outflow spatial and velocity extents and our outflow detection rate imply an outflow duration of $\sim 10^5$ yr.

Subject headings: infrared: stars — ISM: jets and outflows — stars: formation — stars: pre-main-sequence

1. INTRODUCTION

Bok globules are the smallest and simplest molecular clouds. They are nearby dark clouds of gas and dust, usually isolated and displaying simple shapes. Observations of molecular line emission from Bok globules have shown that these clouds are cold ($T_k \sim 10$ K) and often contain small (~ 0.1 pc), dense ($n \sim 10^4$ cm^{-3}) cores. They are the ideal laboratories for studying the conditions leading to the formation of single or a couple of low-mass stars. Until recently, only a handful of globules were known to lodge young stars. In our recent *IRAS* survey of point sources associated with the Bok globules cataloged by Clemens & Barvainis (1988, hereafter CB), we found that a surprisingly large number of Bok globules show evidence for associated point sources (Yun & Clemens 1990, hereafter YC). From a comparison of the 12 and 25 μm fluxes of these objects, we found a distribution of spectral indices consistent with the presence of circumstellar dust, implying that the population is dominated by young stellar objects (YSOs).

Evidence has slowly been accumulating to support the idea that during the early stages of pre–main-sequence stellar evolution, most stars undergo a phase of energetic mass ejection characterized by the occurrence of massive outflows of cold molecular gas (Snell, Loren, & Plambeck 1980; Myers et al. 1988). It has been suggested (Silk & Norman 1980; Schwartz, Gee, & Huang 1988) that the mechanical luminosities of these outflows can be large enough to have pronounced effects on subsequent star formation and the stability of the molecular cloud (cloud support). Further, it has been suggested that outflows might be a mechanism for ejection of the circumstellar material surrounding protostars (Bally & Lada 1983). This process would put an end to accretion onto the forming star, setting limits on the amount of mass that can be accreted, and simultaneously aiding the transition from an embedded, optically invisible object to an optically visible pre–main-sequence star.

Since Lada's (1985) catalog of high-velocity outflows, an increasing number of outflows associated with YSOs in small molecular clouds have been found. These surveys looked for CO outflows near dense cores (Myers et al. 1988) or near pre–main-sequence stars (Levreault 1988). Similarly, Parker, Padman, & Scott (1991) surveyed a set of 12 Lynds (1962) dark clouds showing evidence of embedded *IRAS* point sources. They identified seven new outflows.

In order to search for the presence of outflows associated with our recently discovered YSOs in Bok globules, we conducted a CO survey of these globules using the newly commissioned QUARRY receiver at the Five College Radio Astronomy Observatory. We found evidence for 14 new outflows in our observed sample of 44 YSOs. The presence of outflows seems to occur in the younger, more embedded objects (class I objects in the classification scheme proposed by Lada 1987), as estimated by their 12/25 μm spectral indices. In addition, we found evidence for rotation in five clouds, independent of the presence or absence of outflows.

In the next few sections we present the observations, and discuss and summarize the results of the survey.

2. OBSERVATIONS AND RESULTS

Forty-one small molecular clouds from the CB catalog were surveyed for lines of ^{12}CO at the Five College Radio Astronomy Observatory (FCRAO) during 1991 April 23 to 27. We used QUARRY (*Qua*bbin *Arr*a*y* Receiver), the new 15 beam focal plane array receiver (Erickson et al. 1991), which covered an area of about 4′ × 4′ on the sky. At the observational frequency of 115 GHz, the antenna had beamwidths of 48″ (FWHM). The spectrometer was a 15 × 32 channel 250 kHz filter bank and provided a velocity resolution of 0.65 km s^{-1} channel^{-1}. The rms noise per channel in the final spectra was 0.25 K (T_A^*) or less for a total integration time of 20 minutes at each position. Data for cloud maps were collected in position-switched mode using reference positions previously verified to be emission-free. Pointing was checked by observing

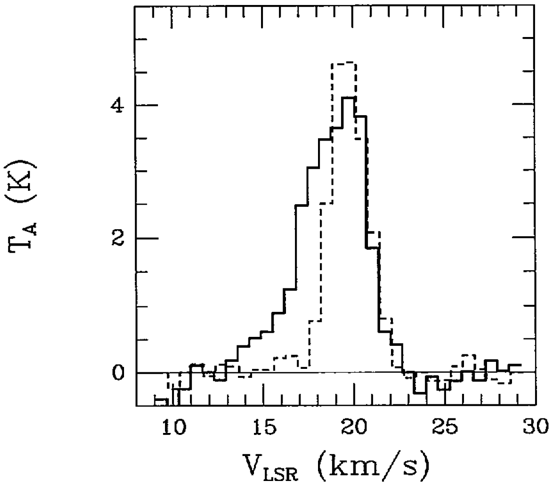

FIG. 1.—Examples of two spectra obtained simultaneously toward CB 54 using QUARRY. One (*dashed line*) shows quiescent cloud material from $\Delta\alpha$, $\Delta\delta = (-1'.7, 0'.8)$; and the other (*solid line*), from $(0'.0, -0'.8)$, exhibits a strong blue wing extending almost 7 km s^{-1} from the line center.

the planets and calibration was done by continuum scanning across Jupiter.

For each globule YSO we collected 45 spectra using three sky placements of QUARRY. The final maps covered approximately 8′ in R.A. and 6′ in decl., with full sampling (48″ × 48″) over a central area of 4′ × 4. After elimination of a few bad channels, linear baselines were fitted and removed from the spectra. Examples of the resulting spectra are shown in Figure 1 for the Bok globule CB 54, where the presence of wings can be seen. Figure 2 shows the contour plot of the blue (*solid lines*) and the red (*dashed lines*) integrated wing emission for the same globule.

In Table 1, the list of the clouds surveyed (col. [1]) and the coordinates of the center of the maps (cols. [2] and [3]) are presented. These coordinates were taken from our list of YSOs found in Bok globules ("YC" in col. [4]), and from the *IRAS* Point Source Catalog (PSC), or CB. The values of the *IRAS* 12 μm and 25 μm fluxes of these YSOs, as found in our study (YC), are also included in Table 1 (cols. [5] and [6]). The values of their spectral indices appear in column (7). We have followed Adams, Lada, & Shu (1987) in defining a spectral index as $\alpha = d \log (\nu S_\nu)/d \log \nu$. As a control group, we have included five globules (CB 12, CB 64, CB 66, CB 68, and CB 100) which do not reveal the presence of a YSO in the YC analysis; these have no entries listed for fluxes or spectral indices.

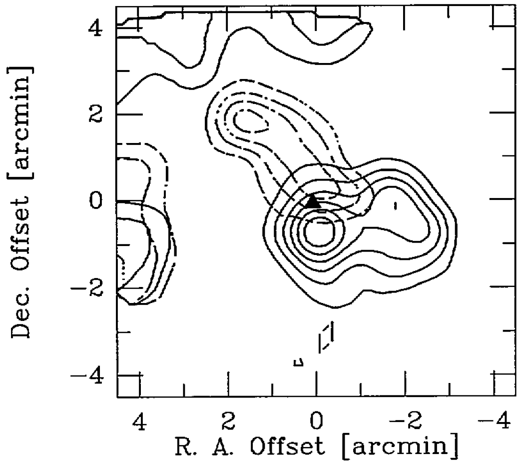

FIG. 2.—Contour plot of the blue (*solid lines*) and the red (*dashed lines*) integrated wing emission for CB 54. Contours begin at 0.25 K km s^{-1} and are stepped by 0.15 K km s^{-1}. The position of the *IRAS* infrared source is marked by a filled triangle.

Outflows were judged to be present when at least some of the CO spectra for a globule were clearly non-Gaussian and displayed wings extending away from the line core. The shape of this line core was determined from spectra seen toward the more quiescent cloud material in each cloud. Contour plots of the wing emission (integrated intensity $\int T_A^* dv$ away from the quiescent line velocities) were also used to identify outflows at the 3 σ sensitivity level.

In Table 2 we list the clouds with detected outflows (col. [1]) as well as estimates of some of their properties; the length scale l (col. [3]) lists an estimate of the spatial extent. This extent is the mean distance from the peak to the half-intensity contour of the integrated high-velocity line wing of the outflow. The velocity Δv (col. [7]) lists the extent of the wings away from the line center to about 0 K. In addition, for the bipolar outflows, we indicate the positions angles (on the sky, east from north) and the positions of the center of the outflows $\Delta\alpha$ and $\Delta\delta$ (offsets from the map centers in Table 1).

Table 3 lists the clouds which exhibit detectable rotation. Rotation was inferred for clouds displaying systematic shifts in the line center velocity with position and whose contour maps of the mean line core velocity revealed symmetric parallel straight lines throughout most of the cloud. Included in the table are estimates of the velocity gradients (col. [2]) and the position angle on the sky of the angular momentum vector (col. [3]).

3. DISCUSSION

The sample of *IRAS* sources surveyed is dominated by low-mass ($\sim$0.7–2 $M_\odot$; YC) YSOs. The spectral indices of these objects indicate, in the nomenclature of the evolutionary sequence proposed by Adams et al. (1987), that they correspond to deeply embedded protostars (class I objects), stars with disks and residual infalling envelopes (class II-D objects), and T Tauri stars with disks but without the surrounding envelope, often optically visible (class II objects).

Thirty-six percent of the globule YSOs surveyed here show evidence for the presence of associated outflows (14 of 39). We will refer to this group of globule YSOs as the outflow group. All but two of the outflow group YSOs have a negative spectral index α corresponding to class I and class II-D objects. The remaining objects (the nonoutflow group) have larger positive spectral indices and showed no outflows to the sensitivity level of our survey. Similarly, we did not detect outflows in any of the control clouds without *IRAS* point sources.

Figure 3 shows the cumulative fraction of sources with spectral indices smaller than or equal to a fixed value. The solid line refers to the nonoutflow group sources; the dashed line refers to the outflow group sources. There is clearly an excess of sources with negative spectral indices in the outflow group compared with the values for the nonoutflow group. Eighty percent of the outflow group sources have $\alpha < 0$. Only about 20% of the nonoutflow group sources have $\alpha < 0$. The probability that the values of α observed for the two data sets (outflow group and nonoutflow group) come from a single

TABLE 1

BOK GLOBULES SEARCHED FOR OUTFLOWS

Cloud (1)	R.A. (1950) (2)	Decl. (1950) (3)	Position Reference (4)	S_{12} (Jy) (5)	S_{25} (Jy) (6)	Spectral Index (7)
CB 3	$00^h25^m59^s$	56°25′32″	PSC	3.67 (0.02)	3.96 (0.02)	0.90
CB 6	00 46 34	50 28 25	PSC	0.20 (0.01)	1.19 (0.01)	−1.43
CB 12	01 35 05	64 50 00	CB	...	...	...
CB 13	01 53 16	62 31 36	YC	0.18 (0.01)	0.15 (0.01)	1.24
CB 28	05 03 45	−04 02 58	PSC	0.47 (0.01)	0.37 (0.01)	1.33
CB 29	05 19 28	−03 43 26	PSC	2.04 (0.02)	2.75 (0.02)	0.59
CB 30	05 26 52	05 38 15	PSC	0.26 (0.02)	0.48 (0.02)	0.18
CB 31	05 30 45	−00 38 15	PSC	1.49 (0.02)	1.92 (0.02)	0.65
CB 32	05 33 48	−00 19 05	PSC	3.37 (0.03)	4.86 (0.03)	0.50
CB 34	05 44 03	20 59 07	PSC	1.65 (0.01)	5.62 (0.02)	−0.67
CB 35	05 44 31	10 23 55	YC	1.45 (0.03)	1.30 (0.02)	1.14
CB 39	05 59 06	16 30 58	PSC	3.87 (0.01)	9.12 (0.01)	−0.17
CB 50	06 31 36	07 49 10	PSC	0.39 (0.01)	0.29 (0.01)	1.41
CB 52	06 46 25	−16 50 38	PSC	0.87 (0.01)	1.04 (0.01)	0.76
CB 54	07 02 06	−16 18 47	PSC	1.76 (0.02)	4.83 (0.01)	−0.37
CB 55	07 02 33	−16 31 49	PSC	0.30 (0.01)	0.10 (0.01)	2.5
CB 58-1	07 15 56	−23 29 36	PSC	0.64 (0.04)	1.08 (0.03)	0.29
CB 58-2	07 16 09	−23 36 11	PSC	0.42 (0.02)	0.75 (0.02)	0.22
CB 64	15 57 35	−01 18 19	CB	...	...	...
CB 66	16 36 41	−14 00 00	CB	...	...	...
CB 68	16 54 24	−16 04 45	CB	...	...	...
CB 81	17 19 19	−27 05 20	YC	0.85 (0.04)	5.39 (0.03)	−1.50
CB 100	17 49 08	−02 58 07	CB	...	...	...
CB 142	18 27 10	−13 42 51	YC	0.89 (0.03)	0.80 (0.02)	1.14
CB 170	18 58 44	−05 33 40	YC	12.96 (0.02)	7.96 (0.02)	1.66
CB 171	18 59 12	−04 38 17	YC	0.31 (0.02)	0.45 (0.02)	0.50
CB 175	18 59 20	−05 22 38	YC	0.26 (0.01)	0.08 (0.01)	2.67
CB 180	19 03 35	−06 56 38	YC	0.73 (0.01)	0.62 (0.01)	1.21
CB 188	19 17 57	11 30 18	YC	0.54 (0.03)	1.64 (0.03)	−0.51
CB 203	19 41 42	18 58 27	YC	0.82 (0.02)	0.88 (0.02)	0.90
CB 205	19 43 22	27 44 01	YC	1.34 (0.02)	5.16 (0.02)	−0.84
CB 206	19 44 23	18 57 49	YC	0.13 (0.03)	0.31 (0.03)	−0.18
CB 214	20 01 54	26 29 42	YC	0.03 (0.01)	0.27 (0.01)	−1.88
CB 216	20 03 45	23 18 25	YC	1.88 (0.02)	5.75 (0.02)	−0.52
CB 217	20 05 55	36 48 14	YC	3.88 (0.11)	5.02 (0.03)	0.65
CB 230	21 16 55	68 04 52	PSC	0.24 (0.01)	0.63 (0.01)	−0.29
CB 232	21 35 14	43 07 05	PSC	1.43 (0.02)	3.80 (0.01)	−0.33
CB 240-1	22 31 46	58 16 26	PSC	0.46 (0.04)	0.98 (0.04)	−0.04
CB 240-2	22 32 08	58 18 28	YC	0.28 (0.04)	0.53 (0.04)	0.12
CB 243	23 22 53	63 20 04	PSC	0.37 (0.01)	0.89 (0.02)	−0.19
CB 244	23 23 49	74 01 08	PSC	0.19 (0.01)	0.68 (0.01)	−0.71
CB 247	23 55 04	64 30 10	PSC	0.17 (0.01)	0.62 (0.01)	−0.74
CB 248-1	23 59 17	47 53 33	YC	0.16 (0.01)	0.18 (0.01)	0.87
CB 248-2	23 59 09	47 48 25	YC	0.11 (0.01)	0.22 (0.01)	0.04

TABLE 2

DETECTED OUTFLOWS

Cloud (1)	Outflow Structure (2)	l (3)	Position Angle (4)	$\Delta\alpha$ (5)	$\Delta\delta$ (6)	Δv (km s^{-1}) (7)
CB 3	Bipolar	0′.8	0°	−0′.2	0′.0	6
CB 34	Bipolar	1.0	−15	0.2	−0.4	5
CB 39	Red	1.2	...	...	...	5
CB 54	Bipolar	1.4	30	0.6	0.4	7
CB 81	Blue	0.6	...	...	...	6
CB 188	Bipolar	1.0	75	−0.4	0.0	5
CB 205	Blue	1.4	...	...	...	7
CB 214	Blue	1.6	...	...	...	5
CB 216	Bipolar	1.2	30	−1.0	0.0	6
CB 217	Red	0.8	...	...	...	5
CB 230	Red	0.6	...	...	...	5
CB 232	Bipolar	1.2	−30	0.2	0.0	4
CB 244	Bipolar	1.0	45	−0.2	−1.0	5
CB 247	Red	1.0	...	...	...	6

parent distribution are about 1 in 10^4 (Kolmogorov-Smirnov test). Together, these findings seem to indicate that the outflow stage occurs early in the pre–main-sequence stellar evolution, before the object appears as an optically visible star (Lada 1988; Terebey, Vogel, & Myers 1989). We also used the CO line widths tabulated by Clemens, Yun, & Heyer (1991, hereafter CYH) to probe the dynamical state of the clouds surveyed

TABLE 3

ROTATING CLOUDS

Cloud (1)	Velocity Gradient Amplitude (km s^{-1} arcmin^{-1}) (2)	P.A. (3)
CB 30	0.6	−45°
CB 34	0.5	90
CB 64	0.3	−60
CB 188	0.1	0
CB 217	0.7	−15

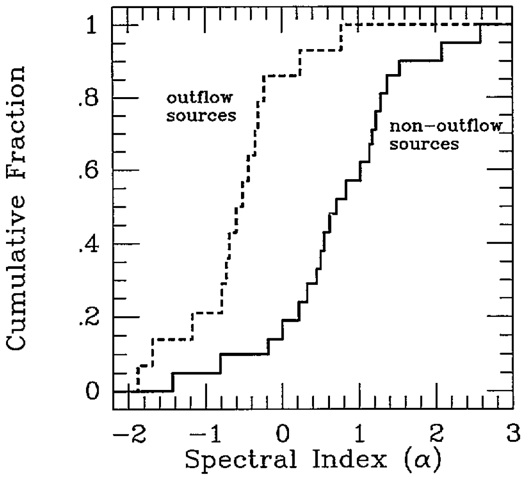

FIG. 3.—Cumulative fraction of sources with spectral indices smaller than or equal to a fixed value. The solid line refers to the nonoutflow group sources; the dashed line refers to the outflow group sources. Notice the large number of sources with negative spectral indices in the outflow group.

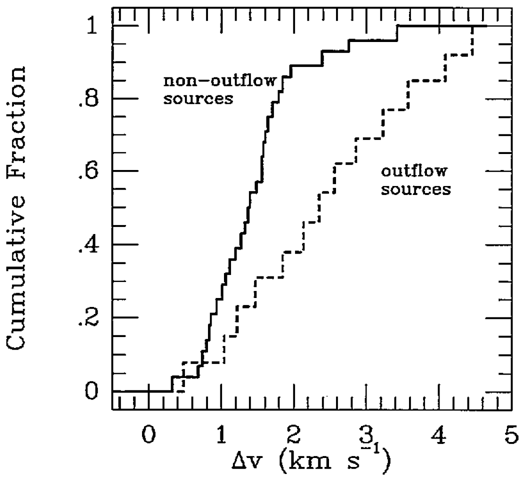

FIG. 4.—Same as Fig. 2 but for the line widths measured by CYH. Ninety percent of the nonoutflow group sources have $\Delta v < 2$ km s^{-1}, while this is the case for only 40% of the outflow group sources.

here. Figure 4 shows that 90% of the nonoutflow group sources have $\Delta v < 2$ km s^{-1}, whereas only 40% of the outflow group sources have $\Delta v < 2$ km s^{-1}. The cumulative fraction of the outflow group reaches 90% for a line width of ~ 4 km s^{-1}. Again using the Kolmogorov-Smirnov test, we infer that the two data sets do not belong to the same parent distribution (99% confidence). We conclude that the outflows seen here typically couple well with the ambient molecular cloud, stirring the gas and producing turbulence that reveals itself in the broadened lines. This conclusion is consistent with the idea that outflows can be responsible for cloud support or dispersal, clearing the material around the forming star, thus setting a limit on the largest mass that can be accreted (Silk & Norman 1980; Myers et al. 1988; Fukui 1989).

The estimates of the velocity and spatial extents (Table 2) can provide an estimate of the dynamical time scale of the outflows detected. For an adopted distance of 600 pc (CB), we obtain time scales of the order of about 10^5 yr. This value is a lower limit due to the combined effects of the projection angle on the sky, and of acceleration. As pointed out by Cabrit & Bertout (1990), these estimates can only be accurate for constant velocity outflows. For accelerated or deaccelerated outflows, time scales so calculated may underestimate the real time scales by an order of magnitude. Using the statistics of our detection rate, we can obtain another estimate of the outflow lifetimes. If we assume that all the YSOs surveyed undergo molecular outflows (detectable at the sensitivity of our survey) at some stage during their early evolution before and during the visible T Tauri star stage, and if we take the duration of this period to be about 10^6 yr (Myers et al. 1987; Wilking, Lada, & Young 1989), we derive an estimate of $\sim 3 \times 10^5$ yr for a typical outflow duration. This result is in good agreement with the results found by Myers et al. (1988) and by Parker et al. (1991).

4. SUMMARY

1. Forty-one Bok globules were surveyed for outflows in the $J = 1$–0 line of ^{12}CO using the new FCRAO QUARRY multibeam receiver. Thirty-six of these globules contain a total of 39 *IRAS* point sources. Of these 39 sources, 14 have CO outflows (detection rate $\sim 36\%$). Of the remaining five control sources (no *IRAS* point sources), none has an outflow.

2. All but two of the sources with outflows have negative infrared spectral indices corresponding to objects in the early stages of pre–main-sequence evolution, before or about to reach the T Tauri stage.

3. The large fraction of outflows detected from globule YSOs is consistent with the idea that most of these YSOs go through an episode of outflow which lasts a large fraction of the pre–main-sequence evolution time.

4. The group of globules with outflows also have gas velocity dispersions significantly greater than the group of globules without outflows. This good mechanical coupling between outflows and the surrounding cloud may be responsible for cloud support, or dispersal and the end of stellar accretion.

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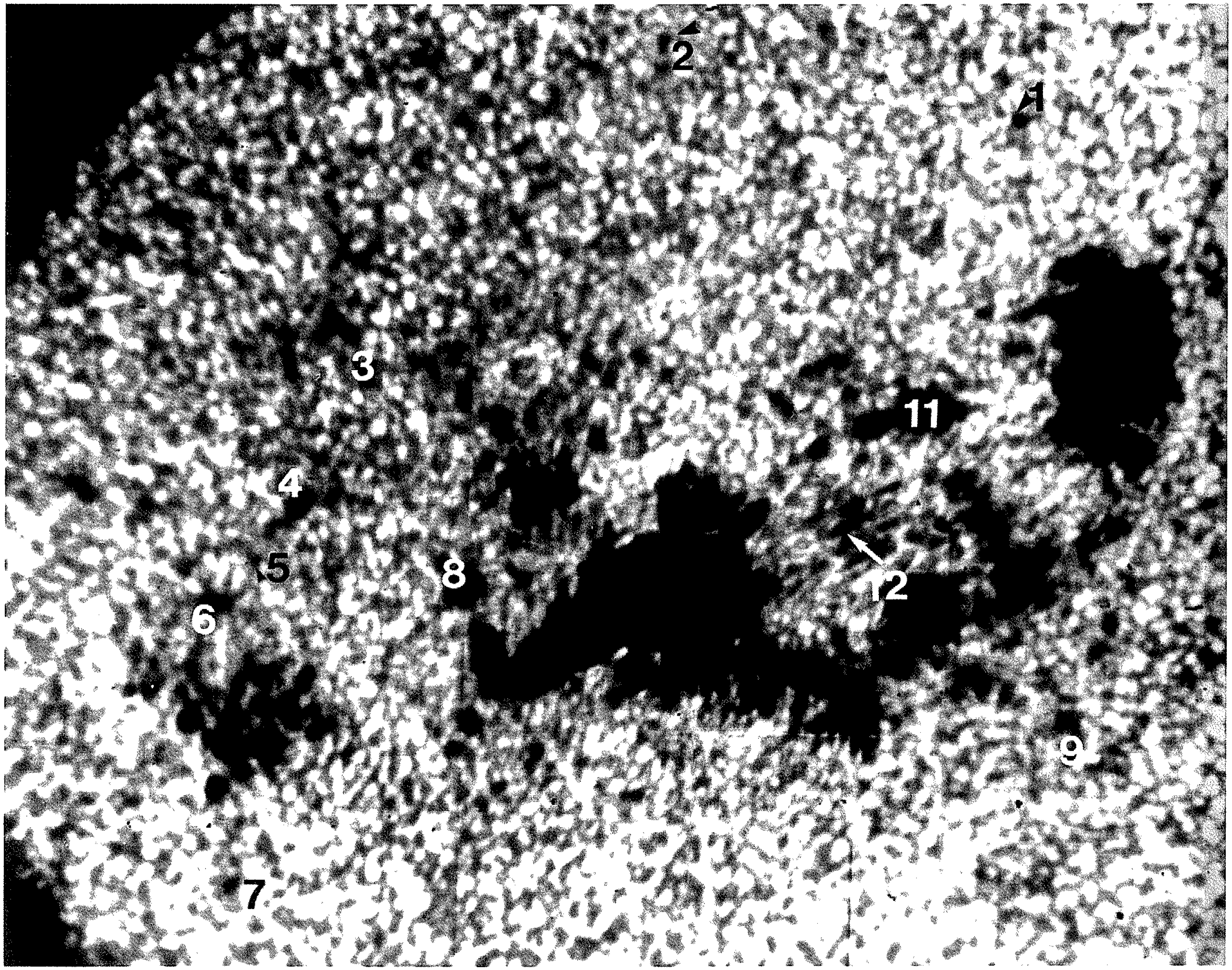

FIG. 1*a*

FIG. 1.—(*a*) Part of the continuum image near 4640 Å and (*b*) videomagnetogram in λ6103 for the 1990 March 22 emerging flux region. Numbers mark some of the corresponding features. Close comparison will reveal many more correspondences than those marked.

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