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HERBIG-HARO OBJECTS IN THE OFF-CORE REGIONS OF THE ρ OPHIUCHI DARK CLOUD

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ABSTRACT

A wide-field survey for Herbig-Haro (HH) objects has been carried out in the ρ Ophiuchi dark cloud, which extends the previous HH-surveyed area in this cloud from 1 deg^2 to 11 deg^2. Besides the confirmation of all the 10 known HH objects in the ρ Oph cloud core (Reipurth, published in 1999), seven groups of HH objects, including HH 548, 549A–C, 550, 551, 552, 553A–E, and 554, are newly discovered in the off-core regions. The newly found HH objects concentrate in three regions, which are 2–3 pc away from the ρ Oph dark cloud core. Among these, the three brightest objects, HH 549, 550, and 551, show characteristic HH morphologies of shock or knot with tail. HH 553 and 554 are located in the L1689N region, but they are unlikely driven by the well-known protostar IRAS 16293−2422. HH 550 and 551 are located more than 1 pc away from the cloud and possibly form a parsec-scale HH flow in Ophiuchus.

Key words: ISM: Herbig-Haro objects — ISM: individual (ρ Ophiuchi cloud) — ISM: jets and outflows — stars: formation — stars: pre–main-sequence

1. INTRODUCTION

The ρ Ophiuchi dark cloud complex is one of the nearest star-forming regions (de Geus, de Zeeuw, & Lub 1989). In the large-scale CO (de Geus, Bronfman, & Thaddeus 1990) and ^{13}CO (Loren 1989a) mappings, it shows two major clumps of gas associated with extended "streamers," as well as the ρ Oph dense core. Within the dense core, over 100 young stellar objects (YSOs; Comerón et al. 1993; Strom, Kepner, & Strom 1995) and seven outflows (Beichman et al. 1986; Tamura et al. 1990; André et al. 1990; Bally & Lada 1983; Loren 1989b; Terebey, Vogel, & Myers 1989; Wu, Zhou, & Evans 1992) have been discovered. Recent submillimeter mapping also revealed outflow cavities (Wilson et al. 1999) and small clumps (Johnstone et al. 2000) in this core.

As an important star-forming tracer, two Herbig-Haro (HH) objects: HH 224 and 79 have been revealed in this cloud (Reipurth & Graham 1988; Wilking, Schwartz, & Blackwell 1987). An HH survey in the central ρ Oph dark cloud was conducted by Wilking, Schwartz, & Fanetti (1997), and three HH objects, HH 312, 313, and 314, were found. Another survey with high spatial resolution in the same region was carried out by Gómez, Whitner, & Wood (1998), and five additional HH objects (HH 416–420) were discovered. The total number of HH objects in this region is then 10 (Reipurth 1999).[5] All these surveys have been restricted to the dense core area of about 1 deg^2, leaving the overall distribution of HH objects and flows in the whole ρ Oph star-forming region unknown. We carried out an imaging survey over an area of about 11 deg^2 centered on the ρ Oph core, through which we expect to reveal the large-scale distribution of HH objects in this active star formation dark cloud. In this paper, we report the observational results in the ρ Oph dark cloud.

2. OBSERVATIONS AND DATA REDUCTION

The observations were carried out using the 60/90 cm Schmidt telescope at the Xinglong Station of the Beijing Astronomical Observatory. The telescope was equipped with a 2048 × 2048 thick Ford CCD at the prime focus of f/3. The field of view of the CCD was $57' \times 57'$, and the pixel size was 15 μm, corresponding to a resolution of $1\farcs67$ pixel^{-1} (Chen 1994; Fan et al. 1996). A narrowband [S II] $\lambda\lambda$6717/6731 filter and a BATC[6] intermediate-band filter [BATC10] were used in our program. The [S II] filter is centered on 6725 Å with a bandpass of 50 Å, and the continuum provided by the [BATC10] filter is centered on 7050 Å with a bandwidth of 300 Å (Deng et al. 2001).

The [S II] and continuum images were acquired during 2000 May 31 to 2000 July 1. Three individual frames for both filters were obtained for each target field, and the exposure times per frame were 20 minutes for the [S II] filter and 5 minutes for the [BATC10] filter. The survey region of 11 deg^2 is covered by 12 target fields in total (ranging from R.A. = 16^h22^m to 16^h35^m and from decl. = $-25°56'$ to $-23°17'$[J2000.0]).

All the data acquired in this survey were processed through the same pipeline programs used in our previous works (Zhao et al. 1999; Wang et al. 2000). For detailed technical description on the pipeline scheme, see Deng et al. (2001).

3. RESULTS

In this survey, all the 10 known HH objects presented by Reipurth (1999) in the ρ Oph core region are confirmed. In addition, seven groups of HH objects were newly discovered outside the core, including HH 548, 549A–C, 550–552, 553A–E, and 554. Coordinates of these newly found HH objects are listed in Table 1. Images in [S II] of these HH objects are shown in Figures 1*a*–1*d*.

HH 548 and 549A–C (Fig. 1*a*) fall in the vicinity of ρ Oph star. HH 548 is a single knot; no infrared source has been

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[5] Available at http://casa.colorado.edu/hhcat.

[6] BATC refers to the Beijing-Arizona-Taiwan-Connecticut Multicolor Sky Survey.

TABLE 1

Newly Discovered Herbig-Haro Objects in ρ Ophiuchi Dark Cloud

O ect	α (J2000.0)	δ (J2000.0)	Angular Size (arcsec)	Comments
HH 548	16 25 18.5	−23 39 03	7	Knot
HH 549A	16 25 30.2	−23 36 00	32	Bow-shaped o ect
HH 549B.......	16 25 39.3	−23 34 56	11	Faint knot
HH 549C	16 25 34.1	−23 34 29	9	Knot
HH 550	16 27 59.3	−25 27 54	50	Bright knot with long tail
HH 551	16 28 17.7	−25 32 37	41	Bright knot with fuzzy ne ula
HH 552	16 27 59.4	−24 57 50	16	Fuzzy ar-shaped o ect
HH 553A	16 31 41.1	−24 29 04	13	Ne ula
HH 553B.......	16 31 39.9	−24 28 15	11	Faint ne ula
HH 553C	16 31 37.1	−24 29 52	8	Faint knot
HH 553D	16 31 36.3	−24 30 05	7	Faint knot
HH 553E.......	16 31 37.3	−24 29 38	7	Faint knot
HH 554	16 31 42.7	−24 31 07	30	Fuzzy ne ula with right core

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

found around it. HH 549A is located 4′ northeast of HH 548. HH 549A outlines a clear HH flow. It is a bright bow shock heading toward the core region. HH 549B appears as a faint nebula, and HH 549C is a knot. Both objects fall in a diffuse nebula. The famous star, ρ Ophiuchi, is situated 8.′5 to the north and along the axis of the HH 549A bow shock. The B-type star ρ Oph excited a bright nebula around it. An emission-line star, IRAS 16226−2319, is located 1.′5 to the

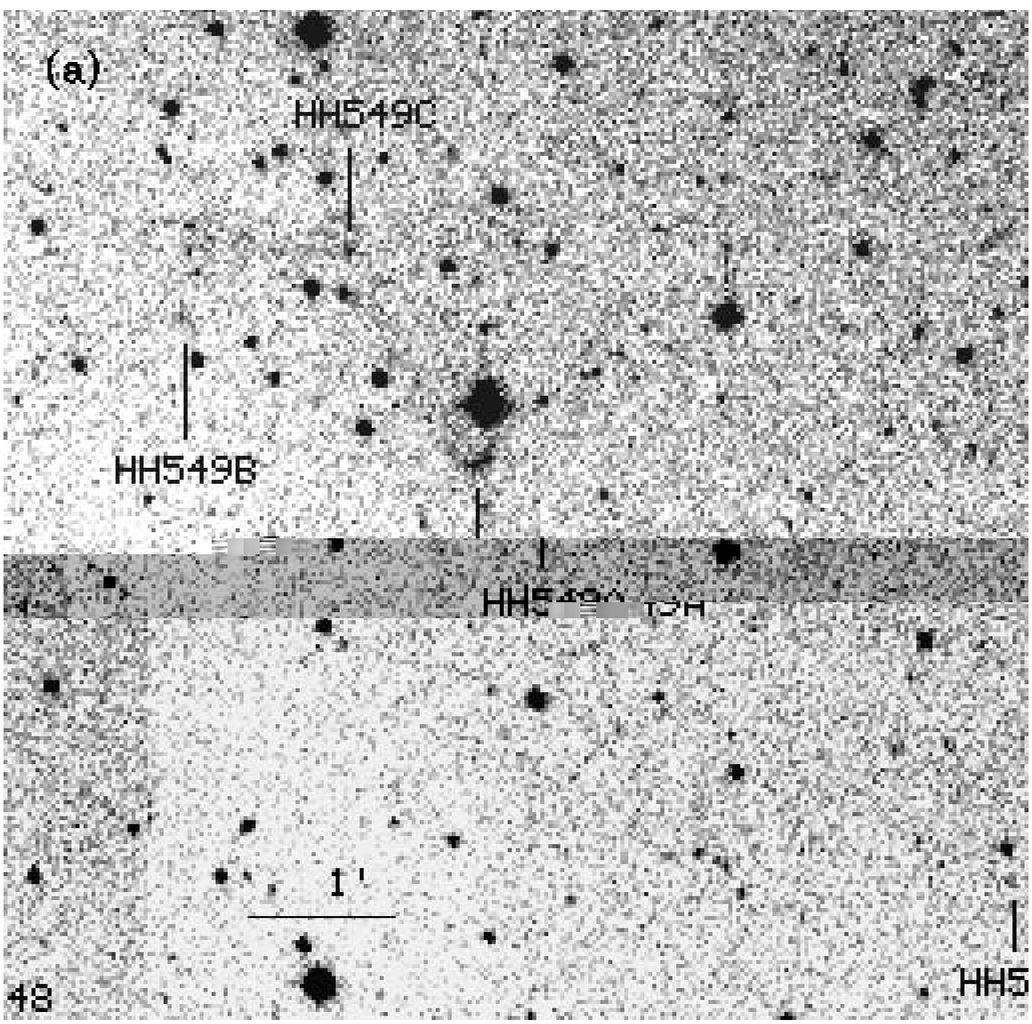


Fig. 1.—[S ii] images of the newly discovered HH objects: (*a*) HH 548 and 549A–C, (*b*) HH 550 and 551, (*c*) HH 552, and (*d*) HH 553A–E and 554. North is up, and east is left.

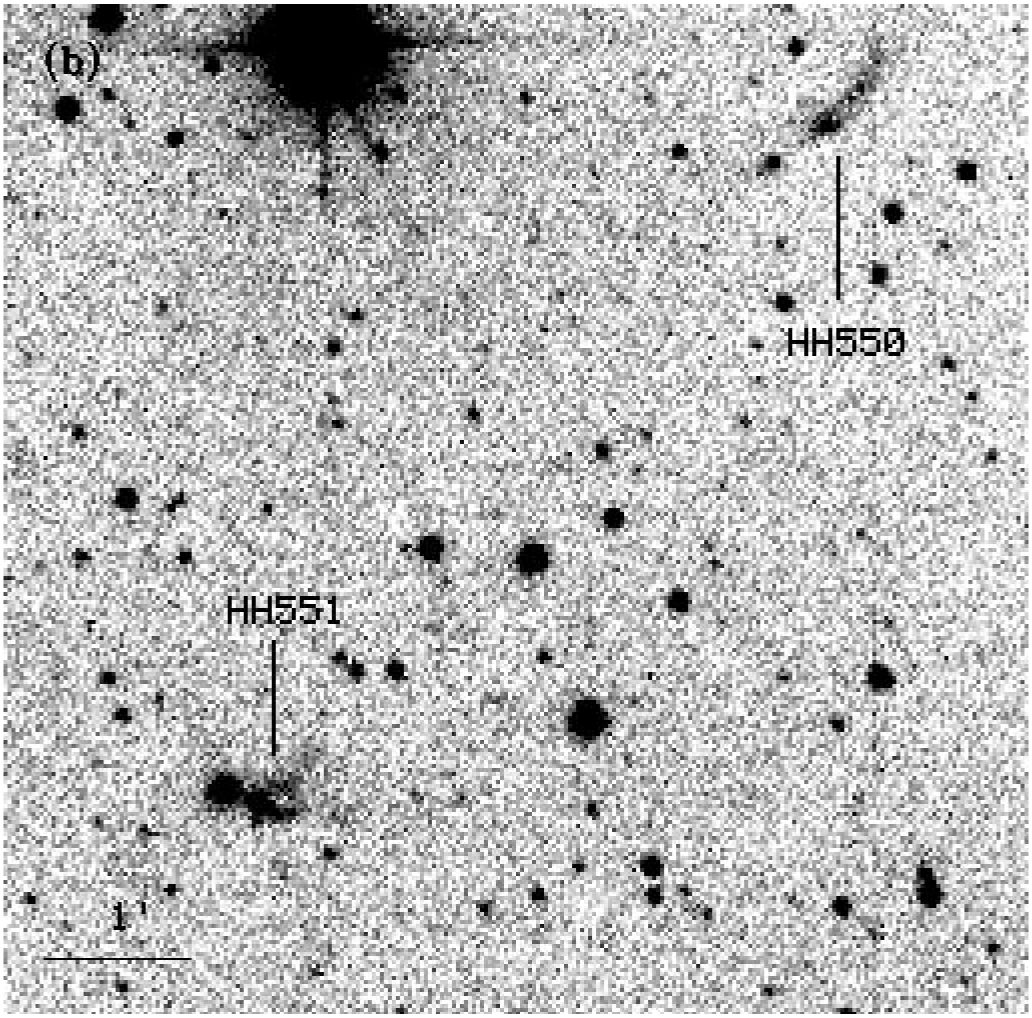


FIG. 1.—*Continued*

northeast of ρ Oph. No other infrared or radio source was detected nearby. On the basis of the morphological relations and the *IRAS* colors, the Hα star IRAS 16226−2319 seems more likely to drive HH 549. The exciting source of HH 549A cannot be surely identified, but it cannot be excluded that the expansion of the H II region of ρ Oph is responsible for the fuzzy bow-shaped [S II] emission. HH 548 is not aligned on the axis of HH 549A flow, and whether it is related to HH 549 is unclear.

HH 550 and HH 551 are more than a half degree away from the south edge of the dark cloud and (Fig. 1*a*) are the brightest HH objects found in this survey. HH 551 is a typical bow shock pointing to the southeast direction. The decreasing wing of the shock extends toward the southeast, where 6′ northwest away is HH 550. HH 550 is also an excellent bow shock having a bright head and a long tail that extends 45° toward the northwest.

No nearby YSO has been found within a 5′ radius of HH 550 and 551. Suggested by the morphology, the driving source of HH 550 and 551 can be traced back to the northwest direction, and they may have the same origin. It is likely that the driving sources are in the far northern region, possibly within the ρ Oph dense core. If this picture holds, considering that HH 550 and 551 are about 40′ (1.5 pc) from the near-side edge of the ρ Oph core, the HH 550/551 case would be the first parsec-scale HH flow in Ophiuchus.

HH 552 (Fig. 1*c*) is a faint elongated object at the south edge of the core region. No infrared source was found near it.

Three weak VLA sources, SFAM 29 and SFAM 163 (Stine et al. 1988) and ROC 29 (André, Montmerle, & Feigelson 1987), sit within 5′ and along the direction of elongation. In the farther north direction is the deeply embedded ρ Oph protocluster (Barsony et al. 1997), and the region is too crowded to identify the energy source.

HH 553A–E are a group of faint HH knots in the L1689N region. The positions of these knots outline a large bow shock heading toward the east, as shown in Figure 1*d*. HH 554 is a bright nebula, slightly separated from the HH 553A–E group. Both HH 553A–E and HH 554 are located about 10′ west of IRAS 16293−2422, the driving source of the ρ Oph E CO outflow (Fukui et al. 1986; Wootten & Loren 1987; Mizuno et al. 1990). IRAS 16293−2422 is a collapsing protostar (Zhou 1999) with a luminosity of 30–40 $L_{\odot}$ (Mundy, Wilking, & Myers 1986; Walker, Adams, & Lada 1990).

Although HH 553A–E and 554 coincide with the general direction of the westward sidelobes of the outflow associated with IRAS 16293−2422, the newly detected HH

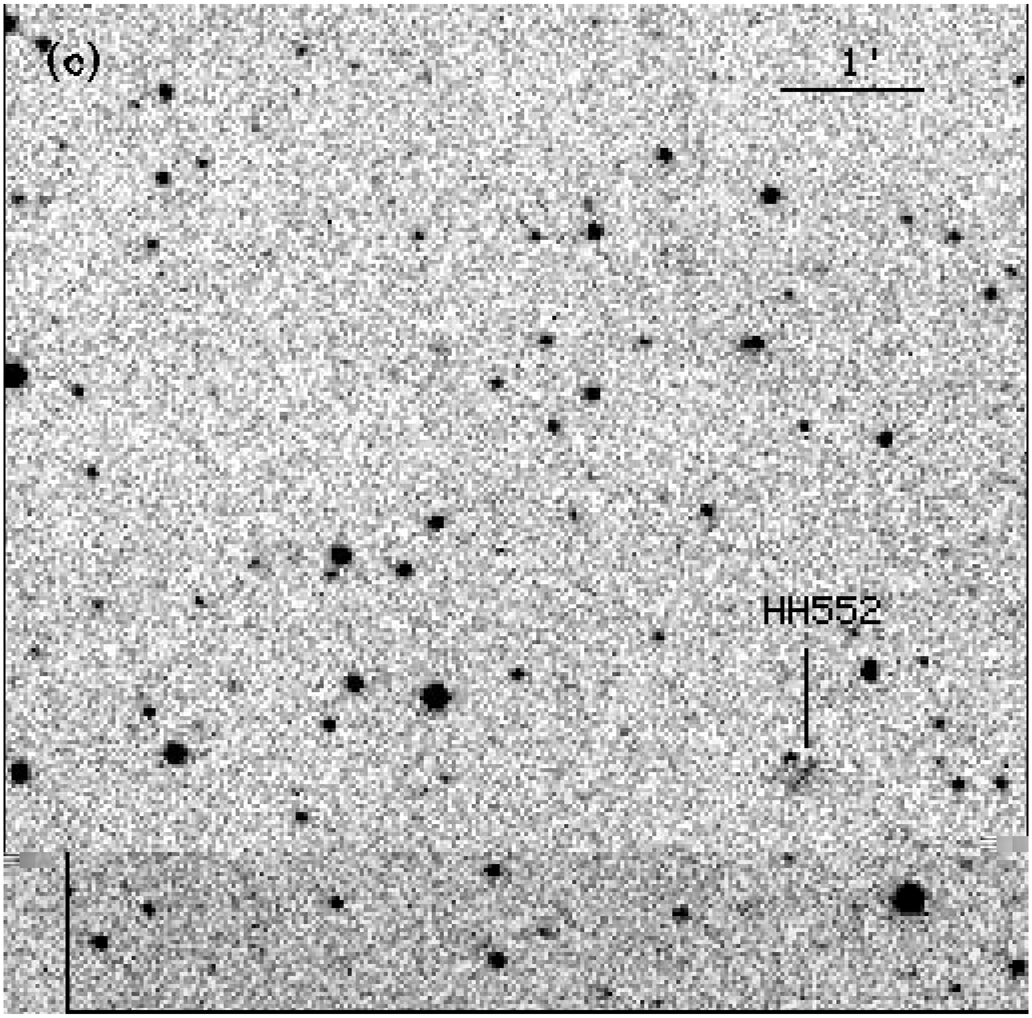


FIG. 1.—*Continued*

objects, especially HH 553A–E, are not perfectly aligned with the western lobes of this molecular outflow. We notice that there are two nearby Hα emission-line sources, IRAS 16284−2418 (WSB 71) and Haro 1-16 (WSB 72), to the north of the HH objects (Wilking et al. 1987). IRAS 16284−2418 (WSB 71) is a binary and Haro 1-16 (WSB 72, IRAS 16285−2421) is a T Tauri star (Herbig & Bell 1988). The distances between Haro 1-16 and HH 553B and E are 120″ and 140″. IRAS 16284−2418 is separated from these two objects by 260″ and 306″, respectively. These distances are far less than those from IRAS 16293−2422, as clearly shown in Figure 2. The bow shock profile apparently formed by HH 553 group can be traced back to the directions of Haro 1-16 and IRAS 16248−2418. The close association suggest that these two Hα emission-line stars are more likely to be the driving sources of HH 553 and 554. Based on current data, we still cannot exclude the possibility that the extremely young source IRAS 16293−2422 is the energy source.

4. DISCUSSION

The ρ Oph dark cloud region is a prototypical area for the study of low-mass star formation in groups. Its dense core region has become the focus of so many surveys and presents rich phenomena including HH objects, outflows, and YSOs showing its high activity. However, for the ample ρ Oph off-core region, its evolutionary condition, including its star formation status is still not very clear. Our large-scale HH object survey provides direct evidence that star-forming activities also exist outside the active dense core, some of which even go up to several parsecs away from the core region. The distribution of the newly found HH objects superposed with the background of ^{12}CO contours (de Geus et al. 1990) is shown in Figure 3. The newly discovered HH objects concentrate in three distinct sites: L1689N, the ρ Oph star area, and HH 550 and 551. The three sites have a similar distance of 2–3 pc away from the dense core.

The case of HH 550 and 551 flow is intriguing; the area of HH 550 and 551 located is far away from the cloud edge. Little gas can be found near them, and no prominent YSO is found nearby. Taking into account their large linear size, high surface brightness, and the orientations of the bow shocks, their energy source should be far away in the north and readily traced back in the dense core. This picture strongly suggests a good sample of a parsec-scale HH flow. There is an increasing number of parsec-scale HH flows from YSOs that are believed to play a very important role in

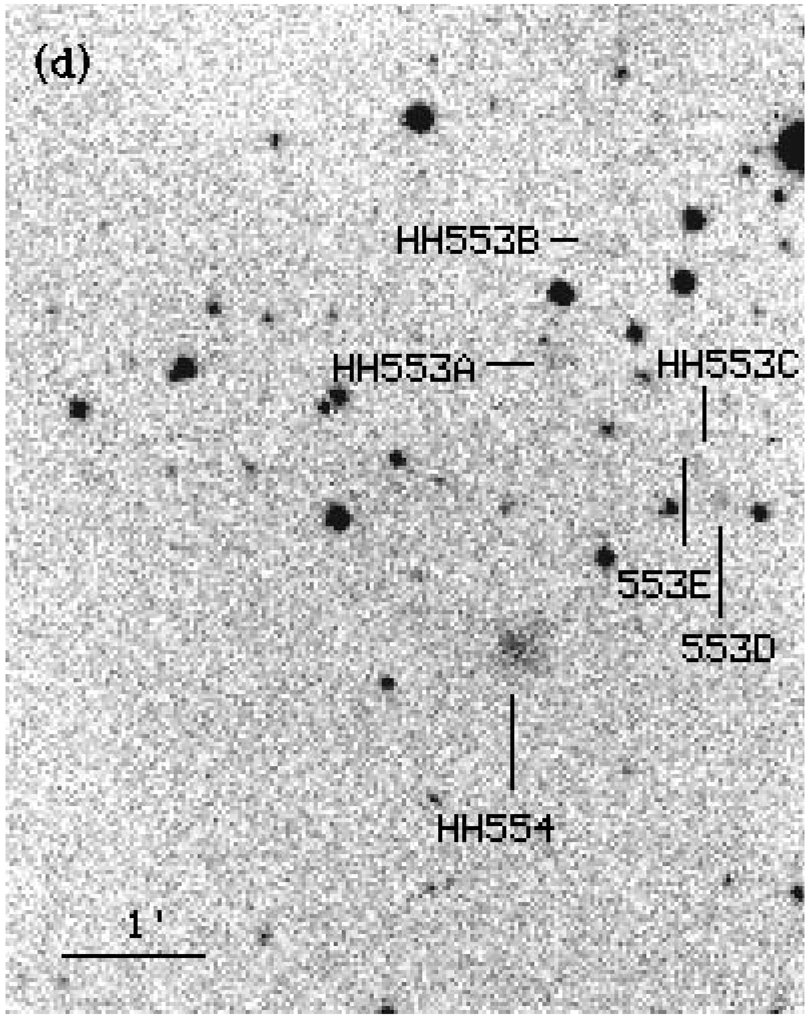
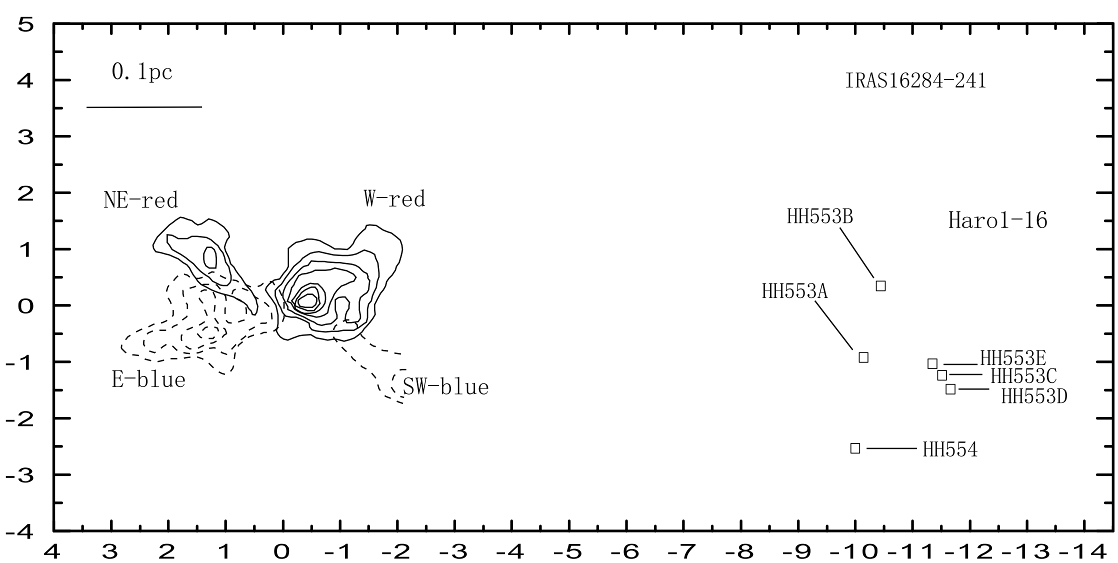


FIG. 1.—*Continued*



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