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A multiwavelength study of young stars in the Elephant Trunk

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Abstract

We present the results of a multiwavelength study of young stars in IC 1396A, "the Elephant Trunk Nebula". Our targets are selected combining optical, near-infrared and mid-infrared photometry. Near-infrared and optical spectroscopy are used to confirm their youth and to derive spectral types for these objects, showing that they are early to mid-M stars, and that our sample includes some of the lowest-mass objects reported so far in the region. The photometric and spectroscopic information is used to construct the spectral energy distributions and to study the properties of the stars (mass, age, accretion, disks, spatial location). The implications for the triggered star formation picture are discussed.

1 Introduction

It has long been suggested that star formation in molecular clouds can be triggered by ionization or shock fronts produced by nearby massive stars (e.g. [7]), yielding to a sequential formation of star clusters in the vicinity of such stars. However, it is not yet clear what is the influence of the enviroment properties (density, mass and size of the cloud, strength of the shock front) in the star formation process, and in particular, in the number, mass distribution and clustering of the forming stars, in the timescales of envelope and disk dissipation, and in the formation of very low-mass objects.

The IC 1396 HII region (d = 800 pc), with a diameter of about 3°, is an ideal site to study triggered star formation. The region, which is being excited by the O6.5f star HD 206267 in its center, contains several young clusters with ages ranging from about 10 Myr

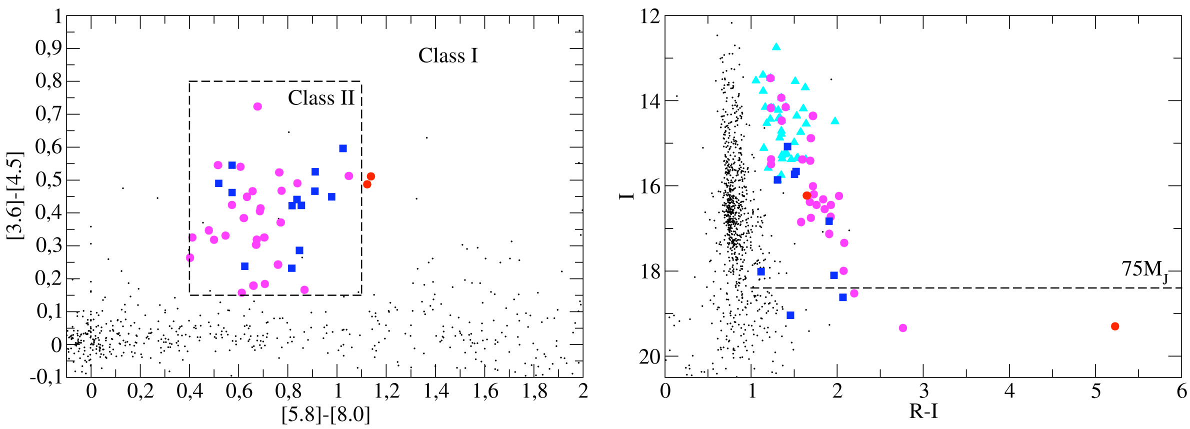

Figure 1: Two of the diagrams used for the candidate selection. Note that only objects detected from R through 8.0 μm are plotted. Our candidate class I and II sources are shown as red and magenta circles, respectively. The blue squares are the candidates with mid-infrared variability from the study by [11]. *Left panel:* IRAC ([3.6] − [4.5], [5.8] − [8.0]) colour-colour diagram, where the locii of class I and II objects are indicated. *Right panel:* (I, $R-I$) colour-magnitude diagram showing the substellar mass limit at the age and distance of IC 1396A. The previously known members of IC 1396A (cyan triangles) define an empirical sequence, used as reference to select new candidate members of the globule (see text).

to less than 1 Myr, and the observed age spread among the stars strongly suggests that star formation is indeed taking place in a sequential fashion (e.g. [16]). Especially interesting is the cometary globule IC 1396A, also called "the Elephant Trunk Nebula", which is located to the west of HD 206267. The globule (∼1 Myr) is adjacent to the older Trumpler 37 cluster (Tr 37, ∼3 Myr), and therefore, two populations of different age coexist in the same area of the sky. The properties of the young stellar population in IC 1396A have deserved much attention in the last decade, and a number of young stellar objects (YSOs), including class I (protostars) and class II sources (young stars with circumstellar disks), have been identified in the region [11, 12, 13, 17].

In this contribution, we present the first results of an ongoing multiwavelength study of young stars in IC 1396A, aiming at building a complete census of the stellar population in the region and at a better understanding of the triggered star formation mechanism.

2 Selection of IC 1396A candidate members

In a recent variability study of protostars in the Elephant Trunk Nebula with *Spitzer*/IRAC photometry, [11] identified 15 new candidate members of this globule showing important mid-infrared variability, probably related to circumstellar dust heating by photospheric hot spots. This work also presented a list of candidate members of IC 1936A selected from their location

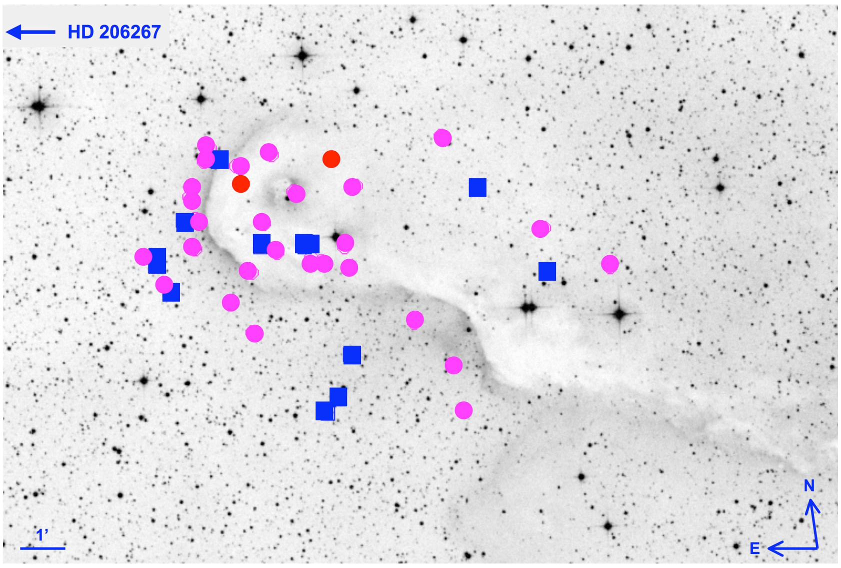

Figure 2: Spatial location of our candidates in the IC 1396A area. Symbols as in Fig. 1. The location of the stars supports their membership to the dark globule, and looks consistent with the picture of triggered star formation (see text).

in a ([3.6] – [4.5], [5.8] – [8.0]) colour-colour diagram like the one showed in the left panel of Fig. 1. Note that this procedure is useful only to identify objects surrounded by circumstellar material (class I and II sources), as young stars without envelopes or disks (class III sources) and field objects are placed in the same area of the colour-colour diagram.

We cross-matched this mid-infrared catalogue with the WFC/INT optical (RIz and Hα) and *Omega*2000/CAHA 3.5m ($JHKs$) near-infrared photometric data from an ongoing campaign in the IC 1396 region. Our optical and near-infrared observations are sensitive to objects down to $I \sim 23$ ($J \sim 20$), the magnitude at which evolutionary models [2, 6] place the hydrogen burning limit for the age and distance of IC 1396A. Therefore, in areas of low extinction, we would expect to identify objects with masses down to the substellar limit.

The IRAC sources with optical and near-infrared counterparts were plotted in several diagrams to discard likely contaminants; the procedure is similar to the one followed by [9] and other works. As an example, the right panel of Fig. 1 shows the (I, $R - I$) colour-magnitude diagram, where the members of the globule define an empirical isochrone to the red of the field objects; all the sources following the prolongation of the empirical sequence to fainter magnitudes, or being located redwards of this sequence, were selected as possible members of IC 1396. This way, a catalogue of 39 probable candidate members of IC 1396A (37 class II and 2 class I sources) with photometric indications of disks and accretion was produced. The list included 10 objects displaying mid-infrared variability according to the study by [11].

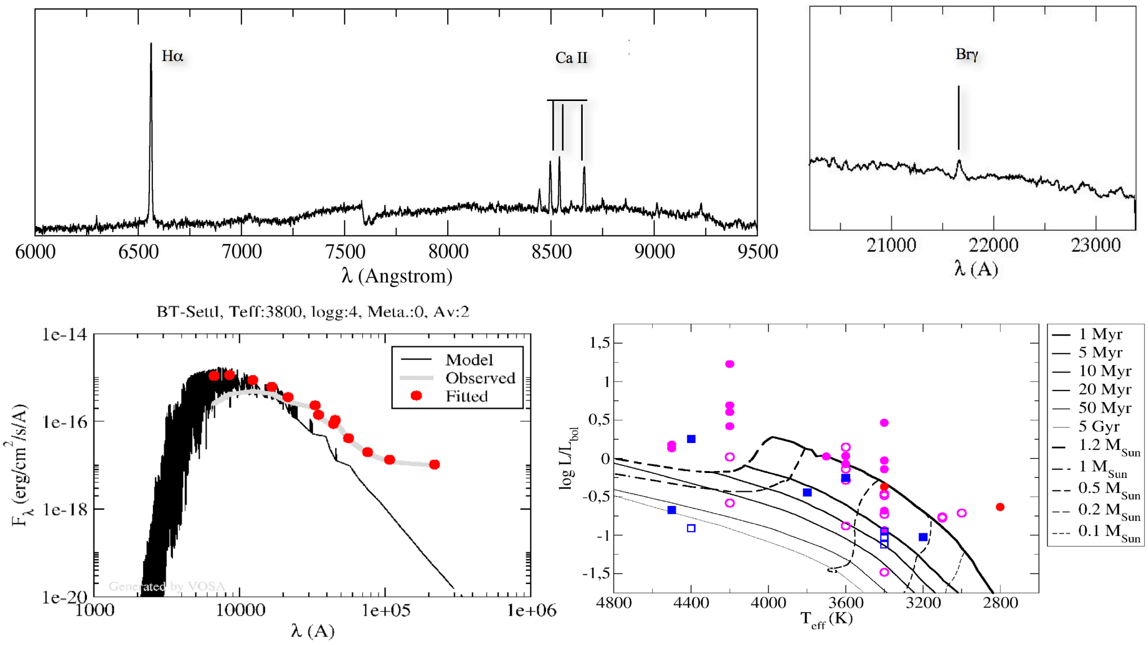

Figure 3: *Upper panels:* Examples of optical and K-band spectra of a low-mass star from our sample displaying strong indications of accretion. *Lower left panel:* The SED fitting confirms that it is an early-M star surrounded by a circumstellar disk. *Lower right panel:* The fitting results are used to plot the objects in a Herzprung-Russell diagram in order to derive their masses and ages. Symbols as in Fig. 1).

3 Properties of the objects

Fig. 2 shows the location of our selected candidates in the IC 1396A area. Most the sources are located within the globule, or at its boundaries in the area recently evaporated by the winds from the nearby O-star HD 206267 to the East (not shown in the image). The least evolved objects (i.e. the class I sources) are located in the most extincted (i.e. dusty) areas. This distribution is consistent with the picture of sequential triggered star formation by the winds of the massive star.

We used the VOSA tool (Virtual Observatory SED Analyzer; [3, 4]) to retrieve complementary photometry for our objects from the Virtual Observatory, and to construct their spectral energy distributions (SEDs). Analysis of the curves confirms the classification of these sources (based on the IRAC colours) as young stars surrounded by different amounts of dust. The SEDs were then fitted to models of stellar photospheres from the Kurucz and BT-Settl grids [5, 1] in order to derive their effective temperatures and bolometric luminosities. In Fig. 3, we show an example of an observed and dereddened SED, along with the best-fitting photosphere for the object.

Using the information from the SED fitting, the sources were plotted in a Hertzprung-Russell diagram to derive masses and ages. According to this analysis, our objects are young

(<10 Myr), and they have masses between 0.2 and 1.4 $M_{\odot}$. Hence, our sample may include some of the least massive stars so far identified in IC 1396A.

4 Spectroscopic follow-up

To confirm the nature of our candidates, two spectroscopic campaigns were carried out. Optical long-slit medium-resolution (R$\sim$1000) spectroscopy of seven objects from our candidate list was obtained with OSIRIS at the GTC. Near-infrared long-slit medium-resolution (R$\sim$1000) spectroscopy of 22 objects was performed with NICS at the TNG; depending on its brightness, each star was observed with one to three grisms, roughly coincident with the K, H and J photometric bands. Four objects were observed both in the optical and in the infrared. We show one example optical spectrum and an example K-band spectrum in Fig. 3.

All the GTC targets display optical spectra characteristic of late-type objects (late-K and early-M stars), especially the TiO molecular bands at around 6200 and 7200 Å. The spectra also show interesting spectral features evidencing accretion or mass loss phenomena (Ca II, [O II], He I). In particular, the Hα line is seen in emission in all of them, with EW(Hα)>10 Å, suggesting it is most likely produced in an accretion shock and not by chromospheric activity. Continuum veiling is also seen in some stars with strong Hα emission.

Analysis of the near-infrared spectra confirms that also the NICS targets are late-type stars (early to mid-M); this is especially clear from the maximum observed around 1.6-1.8 μm in the H-band spectrum, when available. In some cases we temptatively identify some of the H I lines in emission, which are generally associated to accretion.

The spectral accretion signatures are especially prominent in those sources with reported mid-infrared variability, thus reinforcing the hypothesis that this variability is related to accretion rather than to magnetic spots.

5 Conclusions and future work

Using multiwavelength photometry and follow-up spectroscopy, we have identified 41 candidate members of the IC 1396A globule, with estimated masses between 0.2 and 1.4 $M_{\odot}$. Our sample may include some of the least massive stars identified so far in this region. Our objects display indications of strong accretion and mass loss in their spectra. Because several of the spectroscopic targets have reported mid-infrared variability, this reinforces the idea that this variability is caused by accretion. The SED analysis suggests that they are objects in different stages of evolution, and their spatial location is consistent with the expectations according to the sequential triggered star formation picture.

The work has not concluded: We will continue our study of these sources to analyze their disk properties. Spectroscopic follow-up of the sources that could not be observed in the GTC and TNG campaigns is foreseen. We will also study the diskless population in the region, identified with the optical and near-infrared photometry, in order to construct the IMF and to get a more complete picture of the star formation history in the Elephant Trunk

Nebula. The results will be compared with our ongoing optical-near infrared survey of the adjacent Tr 37 cluster.

Acknowledgments

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