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Search for Young Stars and Analysis of Their Properties in the Star-forming Region IC 5146: Postprint

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Abstract

Identifying young stars in star-forming regions is crucial for a comprehensive understanding of the star formation process. This study uses Gaia (Global Astrometric Interferometer for Astrophysics) astrometric data to identify and analyze young stars in the IC 5146 star-forming region. First, Gaia astrometric data is used to verify known young star candidates in this region, confirming that 181 of these candidates are reliable member stars; based on the parallax and proper motion distributions of these 181 confirmed member stars, combined with color-magnitude diagrams, a systematic search is further conducted for the sky area covering IC 5146, finding a total of 290 member star candidates, of which 167 are known member stars and 123 are newly discovered member star candidates. Compared with known member stars, the newly identified member star candidates have a comparable age (both being 1 Myr), but exhibit a lower circumstellar disk fraction (10% vs. 41%) and a lower fraction of variable stars (15% vs. 51%). In terms of spatial distribution, known member stars are primarily distributed in clusters, while newly identified member star candidates are more sparsely distributed, reflecting that both clustered and isolated star formation modes exist in the IC 5146 star-forming region.

Full Text

Preamble

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Search and Property Analysis of Young Stellar Objects in the Star-forming Region IC 5146

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Abstract

The identification of young stellar objects in star-forming regions is essential for a comprehensive understanding of the star formation process. This study uses Gaia (Global Astrometric Interferometer for Astrophysics) astrometric data to identify and analyze young stellar objects in the IC 5146 star-forming region. We first examine known young star candidates in this region using Gaia astrometric data, confirming 181 of them as reliable member stars. Based on the parallax and proper motion distributions of these 181 confirmed members, combined with color-magnitude diagrams, we further conduct a systematic search across the sky area covering IC 5146. In total, we find 290 member star candidates, including 167 known members and 123 newly discovered candidates. Compared with the known members, the newly identified candidates have a comparable age (both approximately 1 Myr) but exhibit lower fractions of circumstellar disks (10% versus 41%) and variability (15% versus 51%). Spatially, the known members are predominantly clustered, whereas the newly identified candidates are more dispersed, reflecting the coexistence of clustered and isolated star formation modes in the IC 5146 region.

Keywords stars: formation, parallaxes, proper motions, protoplanetary disks, Hertzsprung-Russell and color-magnitude diagrams

1 Introduction

Stars form in molecular cloud cores, with the vast majority forming in clusters. Young Stellar Objects (YSOs) refer to stars that have entered the protostellar phase but have not yet evolved to the main sequence. By analyzing stellar photometric data, we can obtain the corresponding Spectral Energy Distribution (SED) and classify YSOs into four types based on SED characteristics: Class 0, I, II, and III, corresponding to different stages in the star formation process. Circumstellar disks are material disks surrounding stars; the gas and dust disks around young stars are called “protoplanetary disks,” produced by angular momentum conservation during the collapse of molecular cloud cores into stars. As YSOs evolve, protoplanetary disks gradually dissipate.

Comprehensive searches for and identification of YSOs in star-forming regions are crucial for measuring the statistical properties of young star populations and estimating star formation rates. YSOs generally exhibit strong X-ray emission, and some also show emission from circumstellar material. Previous studies have often used these observational features to search for YSOs. However, with-

out distance measurements, YSO candidates can be contaminated by non-YSO sources such as broad-line Active Galactic Nuclei (AGN), star-forming galaxies, and Asymptotic Giant Branch (AGB) stars. With the release of Gaia satellite data, a large number of YSOs in nearby star-forming regions now have precise distance and proper motion information, enabling more accurate identification of unknown YSOs by combining these parameters.

The IC 5146 star-forming region consists of an HII region (also known as the Cocoon Nebula) illuminated by a B0V star BD+463474 and two parallel filamentary dark clouds extending westward. Before Gaia data release, previous studies calculated the distance to IC 5146 using various methods including UVB photometry, spectroscopy, infrared photometry, and modern calibrations of absolute magnitudes and colors, but no consensus was reached. IC 5146 has been observed across multiple wavelengths, and numerous YSOs have been discovered in this region. Herbig et al. (2002) identified 380 pre-main-sequence candidates in the cloud region. Harvey et al. (2008) observed the IC 5146 region, including its long filamentary dark clouds, using the IRAC and MIPS cameras on the Spitzer telescope. Through color-magnitude diagrams (CMD) and color-color diagrams (CCD), they identified 202 YSO candidates, which mainly cluster in two small groups: the Cocoon Nebula and the northwest region. This work builds upon these previous YSO candidate samples and combines them with Gaia astrometric data for further study of YSOs in the IC 5146 star-forming region.

In this paper, we use Gaia astrometric and photometric methods to identify candidate members in the IC 5146 molecular cloud, particularly in the outer regions. We also utilize Zwicky Transient Facility (ZTF) survey data, 2MASS (The Two Micron All Sky Survey), and WISE (Wide-field Infrared Survey Explorer) data to obtain stellar properties of these members. Section 2 describes the datasets used in this work, Section 3 details the purification of known member samples and the selection and analysis of newly searched members, and the final section presents our discussion and conclusions.

2 Data

Our sample search is based on the 380 candidate young stars in IC 5146 from Herbig et al. (2002) and the 202 candidate young stars from Harvey et al. (2008) -. We use Gaia, ZTF, 2MASS, and WISE datasets to search for and identify YSOs and analyze stellar properties.

2.1 Gaia Dataset

The Gaia satellite is the European Space Agency' s (ESA) second-generation space astrometry mission. Gaia' s scientific measurements cover three main domains: astrometry (measuring stellar positions, parallaxes, and proper motions), photometry (measuring brightness in multiple bands and epochs), and spectroscopy (obtaining radial velocities and astrophysical parameters). Gaia' s

third data release (Gaia DR3) provides high-precision trigonometric parallaxes and proper motions, which can distinguish stars at different distances and reject field stars with significantly different motions. Additionally, the satellite obtains photometric data that can be used to identify young stars through isochrone fitting.

We first cross-match the coordinates of the 202 YSO candidates from Harvey et al. (2008) [22] with Gaia DR3 using a matching radius of 2 . We apply data quality screening by limiting the Renormalized Unit Weight Error (RUWE) to $\text{RUWE} < 1.4$, following standard practice. This initially yields high-precision parallaxes, total proper motions (pm), right ascension proper motion component (pmra), declination proper motion component (pmdec), G-band mean brightness, and other stellar parameters for 123 known members. Similarly, cross-matching the 380 pre-main-sequence candidates from Herbig et al. (2002) with Gaia ($\text{RUWE} < 1.4$) provides astrometric and photometric data for 320 candidate sources. Based on the purified known YSO sample, we use Gaia DR3 astrometric and photometric data to search and select sources across the entire IC 5146 sky region (RA: 325° - 329° , DEC: 46.867° - 48.067°) [22]. Using the parallax and proper motion parameters of known sources, we preliminarily filter the approximately 260,000 searched sources down to 2,321 candidates.

2.2 ZTF Dataset

The Zwicky Transient Facility (ZTF) is an ongoing time-domain survey project that began in 2018, using a 48-inch Schmidt telescope (P48) at Palomar Observatory to conduct effective survey observations of the northern sky. The telescope is equipped with a camera covering a 47 deg^2 field of view with 16 CCDs (each $6k \times 6k$). This work uses the 18th public ZTF data release (ZTF DR18), which adds two months of observations to DR17, with public data extending to May 7, 2023. The products include 49.6 million single-exposure images, 174,000 stacked images, a source catalog with 76.8 billion source detections extracted from these images, and 4.7 billion light curves constructed from single-exposure images. ZTF provides photometry in g, r, and i bands. We select the r-band mean magnitude and magnitude dispersion values from the photometric data to determine whether sample stars are variable.

2.3 2MASS and WISE Datasets

We use 2MASS and WISE photometric data to determine the presence of circumstellar disks around YSOs. 2MASS used two 1.3 m telescopes to conduct survey observations in three near-infrared bands (J, H, Ks), covering 99.998% of the sky. The wavelengths for the J, H, and Ks bands are 1.25 μm , 1.65 μm , and 2.17 μm , respectively, with limiting magnitudes of 15.8 mag, 15.1 mag, and 14.3 mag. The photometric precision for unsaturated bright sources is about 1-2%, and the positional calibration accuracy is about 100 mas. The all-sky detection data released by 2MASS includes 4.1 million images and approximately 160 million point sources, plus about 1 million extended sources.

WISE is an infrared space telescope that observed 99% of the sky in four bands: W1 (3.4 m), W2 (4.6 m), W3 (12 m), and W4 (22 m). We use the AllWISE catalog, which contains detections of over 700 million sources.

3.1 Purification of Known Member Candidate Samples

By cross-matching the known YSO candidate catalog from Harvey et al. (2008) [22] with the Gaia catalog, we obtain astrometric and photometric information for 123 YSO candidates, hereafter referred to as the Harvey sample. [Figure 1: see original paper] illustrates the purification process for this sample. We perform a Gaussian fit to the parallax distribution of these 123 sources, obtaining a mean parallax of 1.3184 mas (corresponding to a distance of 760 pc) and a standard deviation of 0.1320 mas. We limit the parallax to within 3σ ($0.9224 \text{ mas} < \text{parallax} < 1.7144 \text{ mas}$) to reduce contamination from foreground/background stars at significantly different distances, yielding 102 YSO candidates. The parallax distribution after screening is shown in Figure 1: see original paper.

We then identify reliable cluster members based on proper motion. Figure 1: see original paper shows the proper motion distribution of the 102 known sources. We first perform a 2D Gaussian fit to the distribution and construct a 95% confidence ellipse using the mean, standard deviations, and correlation coefficient, initially rejecting 4 sources outside the ellipse. We then perform a second 2D Gaussian fit on the remaining sources and take the 91 sources within the 95% confidence ellipse of the second fit as reliable members. The mean proper motion from the second Gaussian fit is $\text{pmra} = -2.9891 \text{ mas yr}^{-1}$ and $\text{pmde} = -2.7790 \text{ mas yr}^{-1}$, which we adopt as the cluster's proper motion. This process excludes field stars with significantly different motions from the cluster.

Since YSOs are in the pre-main-sequence stage, we further analyze the 91 known YSO candidates using isochrones. We select theoretical isochrones from the PARSEC library (PAдова and tRieste Stellar Evolutionary Code, Version 2.0) [31] based on Gaia DR3 data. Using the G and G_{RP} bands from Gaia DR3 photometry, we calculate the absolute magnitude in the G band (M_G) from the sources' parallaxes and apparent magnitudes, then construct a color ($G - G_{RP}$) versus magnitude (M_G) diagram. We compare the sample with four isochrones at ages of 0.1 Myr, 0.5 Myr, 1 Myr, and 10 Myr, as shown in Figure 1: see original paper. The distribution reveals that, except for 4 sources, nearly all known YSO candidates lie above or near the 10 Myr isochrone. Note that these data have not been extinction-corrected; after accounting for interstellar extinction, the sample will shift toward the upper-left in the CMD. We will perform extinction corrections in Section 3.2.

Cross-matching the Herbig et al. (2002) pre-main-sequence candidate catalog with the Gaia catalog yields astrometric and photometric data for 320 candidate sources, hereafter referred to as the Herbig sample. We certify members from this sample using parallax, proper motion, and photometric data to obtain more reliable IC 5146 members.

As shown in [Figure 2: see original paper], the Herbig sample exhibits more dispersed proper motion, parallax, and age distributions compared to the Harvey sample, indicating greater contamination. The YSO candidates selected by Harvey et al. (2008) using infrared excess are thus more accurate and reliable. Therefore, using the mean parallax (1.3184 mas) and standard deviation (0.1320 mas) from the Gaussian fit to the Harvey sample's parallax distribution, we retain sources within 3σ of the mean parallax ($0.9224 \text{ mas} < \text{parallax} < 1.7144 \text{ mas}$) from the Herbig catalog, reducing the sample to 170 sources. We further retain only sources whose proper motions fall within the 95% confidence ellipse from the second Gaussian fit of the Harvey sample, narrowing the sample to 127 sources. The proper motion distribution is shown in Figure 2: see original paper, and the parallax distribution in Figure 2: see original paper. Using G and G_{RP} photometry, we calculate absolute magnitudes and construct a color ($G - G_{\text{RP}}$) versus magnitude (M_G) diagram with isochrones at 0.1 Myr, 0.5 Myr, 1 Myr, and 10 Myr, as shown in Figure 2: see original paper. Again, these sources have not been dereddened.

Finally, we merge the 127 certified Herbig sample sources with the 91 Harvey sample sources, obtaining 181 sample sources. In summary, we have used Gaia data to purify the IC 5146 YSO candidates published by Harvey et al. (2008) and Herbig et al. (2002), ultimately obtaining 181 known candidate YSOs in the region.

3.2 Search for New Members and Analysis of Member Properties

In the previous section, we cross-matched the YSO catalogs published by Herbig et al. (2002) and Harvey et al. (2008) with the Gaia catalog, obtaining new high-precision astrometric and photometric parameters to screen YSOs in parallax and proper motion, yielding a subset of reliable candidates. However, the YSO candidate catalog obtained by Harvey et al. (2008) using Spitzer data referenced many earlier studies and searched for candidates within specific regions, biasing the selection toward stars with circumstellar disks and likely missing many diskless young stars. This work uses Gaia data to conduct a systematic search across the entire IC 5146 sky region to identify previously unrecognized YSOs.

We select the entire rectangular sky region of IC 5146 ($325^\circ < \text{RA} < 329^\circ$, $46.867^\circ < \text{DEC} < 48.067^\circ$) [22] as our target and limit $\text{RUWE} < 1.4$, obtaining approximately 260,000 sources from a preliminary Gaia DR3 search. We first constrain the parallax distribution using the range from known members. Based on the mean parallax (1.3184 mas) and standard deviation (0.1320 mas) from the Gaussian fit to the Harvey sample, we limit the searched sample to within 3σ of the mean parallax ($0.9224 \text{ mas} < \text{parallax} < 1.7144 \text{ mas}$), reducing the candidates to 24,009 sources.

We then screen using proper motion parameters fitted from known sources, re-

taining 2,321 sources whose pmra and pmde fall within the 95% confidence ellipse of the Harvey sample' s mean proper motion. This includes 181 known member candidates. [Figure 3: see original paper] illustrates the initial screening process for the newly searched sources, with the proper motion distribution shown in the left panel and the parallax distribution in the right panel.

Variability is an important characteristic of YSOs. Previous studies show that YSOs have higher variability fractions than main-sequence stars, and YSOs with disks have higher variability fractions than diskless YSOs. ZTF time-domain survey data have been widely used to study periodic variability in large samples, including YSO variability properties. We analyze the variability characteristics of stars in the IC 5146 molecular cloud using ZTF multi-epoch photometry. Since r-band photometry is significantly better than g-band and has more observations, our analysis focuses on r-band data.

We extract r-band light curves for all stars in the IC 5146 field from ZTF. We remove high-cadence observations and those with catflags = 32768 (to exclude cloud or moonlight contamination). For sources with at least 20 measurements, we calculate the r-band mean magnitude (\bar{r}) and standard deviation (σ_r). Cross-matching the ZTF sample with our searched sample (2,140 candidate sources and 181 known sources) yields data for 1,919 candidate sources and 171 known sources. [Figure 4: see original paper] shows the relationship between mean magnitude and magnitude dispersion in the light curves, with background grayscale indicating all ZTF sources in the IC 5146 field, red showing newly found candidates, and blue showing known sources. We divide \bar{r} into magnitude bins of 0.32 mag and calculate the mean σ_r ($\bar{\sigma}_r$) within 3σ for all stars in each bin. Interpolating the $\bar{\sigma}_r - \bar{r}$ relationship, the cyan solid line in [Figure 4: see original paper] shows the trend of magnitude dispersion versus mean magnitude for non-variable sources, and the cyan dashed line shows our selection criterion ($2 \times$ the trend). Sources with $\sigma_r > 2\bar{\sigma}_r$ are defined as variable, marked as solid symbols (44 new sources, 92 known sources).

Circumstellar disks emit infrared radiation when heated by the central star, making them observable in infrared bands. We use WISE W1, W2 and 2MASS J, H bands to identify infrared excess emission and estimate circumstellar disk fractions. We cross-match the searched sample (2,140 candidate sources and 181 known sources) with WISE and 2MASS infrared observations using a matching radius of 2', obtaining magnitudes in each band for 179 candidate sources and 100 known sources. The sample sources must meet photometric quality requirements: W1, W2 photometric errors < 0.2 mag, and J, H photometric errors < 0.2 mag.

From Wang & Chen (2019) [42], A_λ denotes extinction magnitude in the corresponding band. Assuming an interstellar reddening law, and using intrinsic colors from Pecaut & Mamajek (2013) [43] for M5-type stars (where "int" denotes intrinsic color: $(J-H)_{int} = 0.70$ mag, $(H-W1)_{int} = 0.96$ mag, $(H-W2)_{int} = 1.52$ mag), we derive the reddening direction for M5-type YSOs from the color excess:

$$\begin{aligned}
E(\text{J-H}) &= (\text{J-H})\{obs\} - (\text{J-H})\{int\} \\
E(\text{H-W1}) &= (\text{H-W1})\{obs\} - (\text{H-W1})\{int\} \\
E(\text{H-W2}) &= (\text{H-W2})\{obs\} - (\text{H-W2})\{int\}
\end{aligned}$$

The extinction law line is defined by $E(\text{H-W1})/E(\text{J-H}) = (A_{\text{H}} - A_{\{\text{W1}\}})/(A_{\text{J}} - A_{\text{H}})$. [Figure 5: see original paper] illustrates our method for selecting sources with infrared excess. Stars to the right of the extinction line show infrared color excess, indicating substantial excess emission above photospheric levels at these wavelengths, likely from circumstellar disks. We identify these as disk-bearing stars. Sources satisfying both conditions in Equation (1) are classified as having disks:

$$\begin{aligned}
[\text{H-W1}] - \sigma_{\text{H-W1}} &> 0.82 \times ([\text{J-H}] + \sigma_{\text{J-H}}) + 0.39 \\
[\text{H-W2}] - \sigma_{\text{H-W2}} &> 0.94 \times ([\text{J-H}] + \sigma_{\text{J-H}}) + 0.86
\end{aligned}$$

In [Figure 5: see original paper], some sources in the lower right are considered diskless because they do not satisfy both conditions simultaneously. Among the newly found candidates, 13/179 (7.3%) harbor circumstellar disks, while among the purified known sample, 69/100 (69%) have disks.

After calculating absolute magnitudes, we construct color ($G - G_{\{\text{RP}\}}$) versus magnitude (M_G) diagrams for the sample sources. Using theoretical isochrones from PARSEC [31] based on Gaia data for different ages, we compare the sample with isochrones at 0.1 Myr, 0.5 Myr, 1 Myr, and 10 Myr. [Figure 6: see original paper] shows the distributions of known sources, variable sources, and disk-bearing sources on the CMD. Red circles in Figure 6: see original paper represent the 2,140 newly searched candidates, while in Figure 6: see original paper and (c) they represent the total sample of 2,321 sources combined with known members. Most newly found sources lie below the 10 Myr isochrone, likely being older field stars. In the three panels, sources above the 10 Myr line comprise 95.6% of the purified known YSO candidates, 76.5% of variable sources, and 95.1% of disk-bearing sources.

Based on the significant differences in sample fractions above and below this isochrone, we select 10 Myr as the age boundary and retain young sources among the new candidates located to the upper right of the isochrone (age < 10 Myr). Since PARSEC models do not extend below the hydrogen-burning limit, we artificially extend the 10 Myr isochrone vertically to include low-mass members. Additionally, because some disk-bearing sources may appear bluer due to accretion activity, we also retain disk-bearing sources in our CMD selection, yielding a total of 352 sources.

The sources shown in [Figure 6: see original paper] have not been extinction-corrected, which may introduce some bias. We therefore perform further extinction corrections on the selected sources to confirm their status as genuine young stars. Most of these sources lack spectroscopic data, so we use multi-band photometry for extinction correction. In addition to Gaia DR3 photometry, we search for measurements in the 2MASS, AllWISE, and Pan-STARRS DR1 catalogs. For sources missing in Pan-STARRS DR1 or lacking certain bands, we

further search SDSS DR16 photometry and Gaia DR3 synthetic catalog SDSS photometry, converting SDSS magnitudes to the Pan-STARRS system using transformations from Tonry et al. (2012) [44]. Of the 352 selected sources, 317 have optical to mid-infrared photometry suitable for extinction correction.

We use main-sequence spectra from the Pickles stellar spectral library (intrinsic colors of main-sequence and pre-main-sequence stars are similar [45]) to generate observed colors at different extinction values. We use 11 color combinations: $G - G_{\text{RP}}$, $J - G_{\text{RP}}$, $H - G_{\text{RP}}$, $K_s - G_{\text{RP}}$, $W1 - G_{\text{RP}}$, $W2 - G_{\text{RP}}$, $g_{\text{ps1}} - G_{\text{RP}}$, $r_{\text{ps1}} - G_{\text{RP}}$, $i_{\text{ps1}} - G_{\text{RP}}$, $z_{\text{ps1}} - G_{\text{RP}}$, and $y_{\text{ps1}} - G_{\text{RP}}$. By comparing observed colors with calculated colors, we determine the best-fit extinction value using minimum chi-squared. For disk-bearing YSOs, disk infrared excess can affect extinction estimates, so we use only 8 color combinations, excluding $W1 - G_{\text{RP}}$, $W2 - G_{\text{RP}}$, and $K_s - G_{\text{RP}}$.

[Figure 7: see original paper] shows the CMD after extinction correction. Some sources move below the 10 Myr isochrone after correction. Some of these have circumstellar disks, and their photometry may be strongly affected by variability, with different catalogs observed at different times, causing color variations that can bias extinction estimates. Additionally, when disk inclination is large, observed emission may come primarily from disk scattering, making colors bluer and luminosities lower. We retain these sources but exclude 27 diskless sources.

Through these steps, we obtain a final sample of 290 sources, including 123 newly found candidate members (red dots) and 167 known YSO candidates (blue dots). In Appendix Table A1, we list the astrometric (coordinates, parallax, proper motion) and photometric (extinction-corrected magnitudes and $G - G_{\text{RP}}$ colors) information for these candidate YSOs, noting known YSOs from previous catalogs and those with variability or circumstellar disks.

4 Discussion

This work presents a detailed study of IC 5146 based on the Gaia point source catalog. Through membership assessment, we screened nearly 260,000 sources from our Gaia search of the entire IC 5146 sky region, ultimately identifying 290 young star candidates, with 123 newly found and 167 previously known.

Comparing the positions of member stars on the CMD with theoretical isochrones, [Figure 7: see original paper] shows that most members have ages between 0.1-10 Myr. [Figure 8: see original paper] fits the mean ages of both samples; using PARSEC isochrones (green solid lines), we estimate average ages of approximately 1 Myr for both the new candidates and known sources. Visual inspection of [Figure 8: see original paper] shows the newly found YSO candidates have a more concentrated age distribution, strictly between 0.5-10 Myr, while known members show more dispersion. Among the new candidates, 10% (13/123) have circumstellar disks and 12% (15/123) show ZTF variability. For known candidates, these fractions are 41% (69/167) and 51%

(85/167), respectively. Disk-bearing YSOs are more likely to be variable [34–38], consistent with the relative fractions in both samples. The earlier member searches were clearly biased toward disk-bearing YSOs, missing many diskless young stars—our work compensates for this deficiency. Note that while we certified 181 known YSO candidates earlier, only 167 appear in the final 290 YSOs because we excluded 14 sources older than 10 Myr without disks after extinction correction.

[Figure 9: see original paper] shows the spatial distribution of our 290 YSOs, overlaid on the Planck 353 GHz intensity map (tracing material distribution in the star-forming region). Blue circles indicate newly searched member candidates, orange shows purified known YSO members, red plus signs mark variable sources, and cyan boxes indicate disk-bearing sources. YSOs on the left side of the image are relatively concentrated, forming a dense cluster in regions where background material is aggregated. YSOs on the right are more dispersed, forming spiral arm-like structures in the periphery where gas and dust are sparser. In addition to the three previously identified clusters (green boxes in [Figure 9: see original paper]), there exists a dense core region (dark red box) with no current active star formation. Compared with previous work, our newly identified YSOs are mostly located in the outer molecular cloud regions beyond the three known clusters, indicating primarily isolated star formation.

Following Casertano & Hut (1985) [46], we calculate the stellar surface density Σ for individual YSOs:

$$\Sigma = (n - 1) / (\pi r_n^2)$$

where r_n is the distance to the n th nearest neighbor. We adopt $n = 6$ as our surface density reference, consistent with Gutermuth et al. (2009) [47]. The resulting surface density distributions for both YSO samples are shown in [Figure 10: see original paper]. The median densities are 53.42 pc^{-2} for known members and 6.28 pc^{-2} for new candidates. Known members have higher surface densities, and combined with [Figure 9: see original paper], we see that newly found YSOs are more dispersed and uniformly distributed throughout the molecular cloud, whereas previous searches concentrated on the clusters.

Gaia DR3 is complete to $G = 19\text{--}20$ mag [48–49]. We adopt $G = 19$ mag as our sample’s completeness limit. At the molecular cloud distance of ~ 760 pc, this corresponds to an absolute magnitude of $M_G = 9.6$ mag. Using PARSEC evolutionary models [31] and considering that YSOs in IC 5146 mainly distribute between 0.1–10 Myr with a concentration around 1 Myr (see CMD in [Figure 7: see original paper]), this absolute magnitude corresponds to a stellar mass of $\sim 0.1 M_\odot$. Using the Chabrier (2003) [50] Initial Mass Function (IMF) with lower limit $0.1 M_\odot$ and upper limit $80 M_\odot$, and considering that 211 sources in our sample are brighter than $G = 19$ mag, we obtain a total stellar mass $M_{\text{star}} = 178 M_\odot$ in IC 5146. Johnstone et al. (2017) [51] derived a molecular cloud mass $M_{\text{cloud}} = 16,000 M_\odot$ using extinction methods. We thus obtain a star formation efficiency (SFE) of $\text{SFE} = M_{\text{star}} / (M_{\text{star}} + M_{\text{cloud}})$

1.1%, about twice the value in Harvey et al. (2008) [22], primarily because we have identified numerous diffusely distributed YSOs, substantially increasing the YSO sample in IC 5146.

5 Summary

Using Gaia DR3 astrometric data, ZTF time-domain survey data, and AllWISE infrared observations, we have searched for YSOs in the IC 5146 molecular cloud and calculated variability and circumstellar disk fractions for the young star sample. We also investigated age characteristics and spatial distribution differences between known and newly identified YSO members. Our main results are summarized as follows:

1. Based on the YSO member samples summarized by Harvey et al. (2008) and Herbig et al. (2002), we used Gaia astrometry to certify known YSO candidates in the IC 5146 molecular cloud, confirming 181 reliable members with mean parallax 1.3184 mas and mean proper motion $\text{pmra} = -2.9891$ mas yr^{-1} , $\text{pmde} = -2.7790$ mas yr^{-1} .
2. Using Gaia DR3 high-precision parallax, proper motion, and photometric data, we re-searched the entire IC 5146 cloud region for member certification, obtaining 290 young star candidates with common distances, motions, and ages (167 known, 123 new).
3. Using ZTF data, we identified 100 variable sources from the relationship between mean magnitude and magnitude dispersion. Combined with the AllWISE point source catalog, we identified 82 sources with circumstellar disks via infrared excess. The new sources contain more diskless and non-variable members.
4. Fitting isochrones to the extinction-corrected color-magnitude distribution shows both samples have average ages of approximately 1 Myr, with the new sources having a more concentrated age distribution.
5. Examining the spatial distribution reveals that previous searches concentrated on clusters in this region. Combined with stellar surface density calculations, known members have higher surface densities than newly found members, which are more dispersed and uniformly distributed throughout the molecular cloud.
6. Using the Chabrier (2003) IMF, we calculate a total stellar mass $M_{\text{star}} = 178 M_{\odot}$ in the IC 5146 region. Based on Johnstone et al. (2017) extinction measurements giving $M_{\text{cloud}} = 16,000 M_{\odot}$, we derive a star formation efficiency of $\sim 1.1\%$, twice the previous result.

Our study of IC 5146 suggests that beyond the few known YSOs, many more candidate members may remain unobserved. Statistically, compared to previously published candidates by Harvey et al. (2008) and Herbig et al. (2002)

(reliable members concentrated in three cluster cores), most of our newly identified YSOs are located in the outer molecular cloud regions beyond the clusters.

Previous YSO searches primarily selected candidates based on infrared excess, which was always contaminated by non-YSO sources and missed many young stars without infrared excess. The Gaia catalog serves as a powerful tool for searching for YSOs and exploring their evolutionary states, advancing our understanding of star formation.

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Appendix Table A1

Table A1 Properties of YSO candidates in the IC 5146 molecular cloud

DR3Name	RA (J2000)/°	DEC (J2000)/°	Parallax/ (mas)	pmra/(mas yr ⁻¹)	pmde/(mas yr ⁻¹)	M_G	log(RPK/mag)	log(K/mag)
...

Note: The complete table with all 290 sources is presented in the Appendix.

Note: Figure translations are in progress. See original paper for figures.

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