A Census of the 32 Ori Association with Gaia*

K. L. Luhman1,2

1 Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA; kl207@psu.edu
2 Center for Exoplanets and Habitable Worlds, The Pennsylvania State University, University Park, PA 16802, USA

Received 2022 June 14; revised 2022 July 30; accepted 2022 July 31; published 2022 September 21

Abstract

I have used high-precision photometry and astrometry from the third data release of Gaia (DR3) to identify candidate members of the 32 Ori association. Spectral types and radial velocities have been measured for subsets of the candidates using new and archival spectra. For the candidates that have radial velocity measurements, I have used UVW velocities to further constrain their membership, arriving at a final catalog of 169 candidates. I estimate that the completeness of the survey is ~90% for spectral types of \( \lesssim M7 \) (\( \gtrsim 0.06 \, M_{\odot} \)). The histogram of spectral types for the 32 Ori candidates exhibits a maximum at M5 (\( \sim 0.15 \, M_{\odot} \)), resembling the distributions measured for other young clusters and associations in the solar neighborhood. The available UVW velocities indicate that the association is expanding, but they do not produce a well-defined kinematic age. Based on their sequences of low-mass stars in color–magnitude diagrams, the 32 Ori association and Upper Centaurus-Lupus/Lower Centaurus-Crux (UCL/LCC) are coeval to within \( \pm 1.2 \) Myr, and they are younger than the \( \beta \) Pic moving group by \( \sim 3 \) Myr, which agrees with results from previous analysis based on the second data release of Gaia. Finally, I have used mid-IR photometry from the Wide-field Infrared Survey Explorer to check for excess emission from circumstellar disks among the 32 Ori candidates. Disks are detected for 18 candidates, half of which are reported for the first time in this work. The fraction of candidates at \( \lesssim M6 \) that have full, transitional, or evolved disks is 10/149 = 0.07\( \pm 0.03 \), which is consistent with the value for UCL/LCC.

Key words: Brown dwarfs – Star formation – Initial mass function – Low mass stars – Stellar associations – Circumstellar disks – Protoplanetary disks

Supporting material: data behind figure, machine-readable tables

1. Introduction

The identification of members of nearby young associations (\( \lesssim 100 \) pc, \( \lesssim 100 \) Myr) is important for studies of the formation and early evolution of stars and planets (Zuckerman & Song 2004; Torres et al. 2008). Surveys for association members have utilized multiple approaches, which have consisted primarily of the following: (1) selecting candidates for young nearby stars from all-sky surveys in X-rays or UV emission (Kastner et al. 1997, 2017; Mamajek et al. 1999; Webb et al. 1999; Torres et al. 2000; Zuckerman et al. 2001b; Shkolnik et al. 2009, 2012; Rodríguez et al. 2011, 2013; Bowler et al. 2019; Binks et al. 2020), confirming their youth with spectroscopy, and identifying the associations to which they might belong with available kinematic data; (2) selecting candidate members of specific associations via photometry and proper motions from wide-field imaging surveys (Song et al. 2004; Malo et al. 2013; Gagné et al. 2014b; Elliott et al. 2016; Riedel et al. 2017; Shkolnik et al. 2017; Schneider et al. 2019), sometimes in conjunction with X-ray and UV emission (Schieder et al. 2010, 2012b, 2012c; Binks et al. 2015, 2018; Binks & Jeffries 2016), and confirming their youth with spectroscopy; (3) selecting candidates for late-type dwarfs with photometry from wide-field infrared (IR) surveys, confirming their cool nature via spectroscopy, and obtaining kinematic data for objects with spectral evidence of youth to assess membership in young associations (Rice et al. 2010; Delorme et al. 2012; Liu et al. 2013, 2016; Kellogg et al. 2015; Schneider et al. 2014, 2016; Burgasser et al. 2016; Best et al. 2017; Bardalez Gagliuffi et al. 2018; Gagné et al. 2018a); and (4) selecting candidates for late-type members of associations via IR photometry and proper motions from wide-field surveys and confirming their youth and cool nature with spectroscopy (Gagné et al. 2014a, 2014b, 2014c, 2015a, 2015b, 2015c, 2017, 2018c; Aller et al. 2016). Parallax measurements from the Hipparcos mission also have been utilized in the identification of the brightest members of associations (Zuckerman & Webb 2000; Zuckerman et al. 2001a). These surveys have produced hundreds of candidate members of nearby associations, although it is likely that there remains significant incompleteness, particularly among low-mass stars and brown dwarfs.

Progress in cataloging the members of nearby associations has been driven by advances in wide-field photometric and astrometric surveys. That progress has been especially rapid in recent years owing to the Gaia mission (Perryman et al. 2001; de Bruijne 2012; Gaia Collaboration et al. 2016), which is performing an all-sky survey to measure high-precision photometry, proper motions, and parallaxes for more than a billion stars as faint as \( G \sim 20 \). Gaia data have been used to identify both new associations in the solar neighborhood (Oh et al. 2017; Faherty et al. 2018; Gagné et al. 2018b; Kounkel & Covey 2019; Meingast et al. 2019) and new candidate members of known associations (Gagné et al. 2018d; Gagné & Faherty 2018; Lee & Song 2019; Zuckerman et al. 2019; Ujijwal et al. 2020).

* Based on observations made with the Gaia mission, the Two Micron All Sky Survey, the Wide-field Infrared Survey Explorer, the LAMOST survey, the Sloan Digital Sky Survey IV, the NASA Infrared Telescope Facility, and Cerro Tololo Inter-American Observatory.

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
In this paper, I present a survey for members of the association containing the B5 star 32 Ori (Mamajek 2007; Burgasser et al. 2016; Bell et al. 2017) using the third data release of Gaia (DR3; Gaia Collaboration et al. 2021, 2022). I have used astrometry and photometry from Gaia DR3 to identify candidate members of 32 Ori (Section 2) and have performed spectroscopy on a subset of those candidates to measure their spectral types, diagnostics of youth, and radial velocities (Section 3). For the candidates with measured radial velocities, membership is further constrained using U/V/W velocities (Section 4). I compare my final catalog of candidates to previous membership studies of 32 Ori (Section 5), and I use it to study the association in terms of its initial mass function (IMF), kinematic and isochronal ages, and circumstellar disks (Section 6).

2. Identification of Candidate Members

2.1. Kinematic Selection Criteria

The analysis in this study was initially based on the second data release of Gaia (DR2) and was updated with Gaia DR3 when it became available. The Gaia data employed in my analysis consist of the following: photometry in bands at 3300–10500 Å ($G$), 3300–6800 Å ($G_{BP}$), and 6300–10500 Å ($G_{RP}$); proper motions and parallaxes ($G \lesssim 20$); radial velocities ($G \lesssim 14$); and the renormalized unit weight error (RUWE; Lindegren 2018). The latter provides a measure of the goodness of fit for the astrometry. As in my previous work with Gaia data (e.g., Luhman & Esplin 2020; Luhman 2022a), I adopt a threshold of RUWE < 1.6 when selecting astrometry that is likely to be reliable.

Since radial velocity data are available for only a small fraction of the stars from Gaia DR3 that have proper motion and parallax measurements, I rely on the latter parameters for the initial kinematic selection of candidate members of 32 Ori. To reduce projection effects, I analyze the Gaia astrometry in terms of a “proper motion offset” ($\Delta \mu_{o,\alpha}$), which is defined as the difference between the observed proper motion of a star and the motion expected at the celestial coordinates and parallactic distance of the star for a specified space velocity (e.g., Esplin & Luhman 2017; Luhman & Esplin 2020; Luhman 2022a). In this study, the proper motion offsets are calculated relative to the motions expected for a space velocity of $U, V, W = -12, -19, -9$ km s$^{-1}$, which approximates the median velocity of 32 Ori members (Bell et al. 2017, Section 4). For parallactic distances, I adopt the geometric values estimated by Bailer-Jones et al. (2021) from DR3 parallaxes.

To develop kinematic criteria for selecting candidate members of 32 Ori from Gaia DR3, I began by considering the 46 proposed members from Bell et al. (2017). Parallax measurements are available from Gaia DR3 for 44 of those 46 sources. The objects that lack parallaxes consist of 2MASS J05235565+1101027 (M5; Bell et al. 2017) and WISE J052857.68+090104.4 (L1; Burgasser et al. 2016); the former is in Gaia DR3, while the latter was not detected by Gaia. The candidates with parallax data are plotted in diagrams of proper motion offsets versus parallactic distance in the top row of Figure 1. Among the 32 stars with RUWE < 1.6, 27 are well clustered in those parameters and are plotted with one symbol, while the remaining five stars are outliers and are plotted with a second symbol. Stars with RUWE $\geq$ 1.6 are shown with a third symbol; three are well clustered, and nine are outliers (three are beyond the limits of the diagrams). The five outliers with RUWE < 1.6 consist of 32 Ori A, THOR 9A, THOR 26, THOR 16, and THOR 34. The latter three also appear below the sequence formed by the well-clustered stars in color–magnitude diagrams (CMDs) constructed from Gaia photometry (Section 2.2), so they are classified as nonmembers in this work. Although they have low RUWE, the astrometry of 32 Ori A and THOR 9A could have errors that are caused by their companions, so they are retained as candidate members.

During the application of preliminary kinematic criteria based on the 32 Ori members from Bell et al. (2017), I realized that the small group associated with the B8 star 118 Tau from Mamajek (2016) is spatially adjacent to the 32 Ori sample and shares a roughly similar space velocity, indicating that the stars near 32 Ori and 118 Tau may be members of the same association. Therefore, I also considered the 11 candidate members of the 118 Tau group from Mamajek (2016) when designing the final selection criteria. The proper motion offsets and distances of those stars are shown in the bottom row of Figure 1, where stars with RUWE < 1.6 and RUWE $\geq$ 1.6 are plotted with different symbols. The nine stars with RUWE < 1.6 have similar offsets and distances to the 32 Ori candidates. For my survey, I have adopted $|\Delta \mu_{o,\alpha}| < 4$ mas yr$^{-1}$ as selection criteria for new candidates, which encompass all of the well-clustered 32 Ori and 118 Tau candidates in Figure 1. I applied those $\Delta \mu_{o,\alpha}$ criteria and the photometric criteria from Section 2.2 to the Gaia DR3 catalog for ranges of equatorial coordinates and distance that are large enough to encompass the well-clustered 32 Ori and 118 Tau candidates in Figure 1, and I expanded those ranges until few additional candidates were identified by additional expansion. Based on that analysis, I have adopted 50°–90°, 0°–45°, and 70–120 pc as selection criteria for R.A., decl., and distance, respectively. In the left panel of Figure 2, the previously proposed members of 118 Tau and 32 Ori are plotted on a map of equatorial coordinates for that survey field. In addition, I have required that candidates have RUWE < 1.6 and $\sigma_{\pi} < 1$ mas. I have retrieved from Gaia DR3 all sources that satisfy the preceding selection criteria, resulting in a sample of 244 candidates after the stars from Mamajek (2016) and Bell et al. (2017) are excluded.

In Section 4, analysis of the space velocities of candidates from this survey demonstrates that the previous samples associated with 118 Tau and 32 Ori do indeed reside within a single association. Since 32 Ori has an earlier spectral type than 118 Tau, I have adopted the former as the name for the association. For the remainder of this study, I refer to the 118 Tau group only when specifying the sample of stars from Mamajek (2016).

2.2. Photometric Selection Criteria

The candidate members of the 32 Ori association selected via kinematics in the previous section can be further refined with CMDs. In the top row of Figure 3, I present CMDs of $M_{G_{RP}}$ versus $G_{BP} - G_{RP}$ and $G - G_{RP}$ for the previously proposed members of 118 Tau and 32 Ori that have RUWE < 1.6, excluding photometry with errors greater than 0.1 mag. The 32 Ori stars are plotted with symbols based on whether they are outliers in Figure 1. As mentioned in the previous section, three of the 32 Ori kinematic outliers appear below the sequences formed by the other members and hence are rejected as nonmembers. Although the number of 118 Tau candidates is
small, their positions in the CMDs are consistent with the same age as the 32 Ori candidates if they consist of a mixture of single stars and unresolved binaries. Through analysis of Gaia DR2 CMDs, Luhman & Esplin (2020) found that the 32 Ori members from Bell et al. (2017) have a similar age to Upper Centaurus-Lupus/Lower Centaurus-Crux (UCL/LCC), which is one of the oldest populations in the Scorpius-Centaurus (Sco-Cen) OB association (∼20 Myr). In Figure 3, I have included the boundaries that Luhman (2022a) used for selecting photometric candidates in UCL/LCC and other populations in Sco-Cen. Those boundaries closely follow the lower envelopes of the sequences of previously proposed members of 32 Ori and 118 Tau, so they are used for selecting candidates in this survey as well.

The bottom row of Figure 3 shows CMDs for the kinematic candidates selected in the previous section. In each CMD, the candidates form two distinct populations that consist of stars near the main sequence and a brighter band of stars that aligns with the sequence of previously proposed members of 32 Ori and 118 Tau. A few stars appear within the sequence of young stars in the \( G_{\mathrm{BP}} - G_{\mathrm{RP}} \) CMD but are much redder than that sequence in the \( G - G_{\mathrm{RP}} \) CMD, which is likely a reflection of erroneous photometry in \( G \) due to contamination from a close companion (Evans et al. 2018). I have rejected kinematic candidates that appear below the boundary from Luhman (2022a) in either CMD unless they exhibit IR excess emission in photometry from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010). Stars with IR excesses are retained because an excess may indicate the presence of a disk, and a disk-bearing star can appear underluminous in a CMD if the disk is edge-on or if accretion-related emission is present at shorter optical wavelengths. Two candidates appear below the CMD boundaries and exhibit IR excess in photometry from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010). These photometric criteria are satisfied by 122 of the 244 kinematic candidates.

When I combine the 122 candidates with the 36 previously proposed members of 118 Tau and 32 Ori that have RUWE < 1.6 and are well clustered in Figure 1 (Section 2.1), I arrive at a sample of 158 candidate members. In Figure 4, I have plotted that sample in diagrams of \( \Delta \mu_\alpha \) versus R.A. and distance and \( \Delta \mu_\delta \) versus decl. and distance. The candidates exhibit a correlation between \( \Delta \mu_\delta \) and decl., which is suggestive of expansion in that direction. In Sections 4 and 6.2, evidence of expansion is investigated in more detail using the \( UVW \) velocities for the candidates that have radial velocity measurements.

2.3. Additional Candidates

In the previous section, I identified 158 stars that satisfy kinematic and photometric criteria for membership in 32 Ori. In this section, I describe 17 additional stars that are included in my catalog of candidates.
As discussed in Section 2.1, two of the proposed members of 32 Ori from Bell et al. (2017), 32 Ori A and THOR 9A, are kinematic outliers in Figure 1 but are retained as candidates because their astrometry may be affected by companions. THOR 10, THOR 32, THOR 8A, HHJ 430, Gaia DR3 3284091290564991104, and Gaia DR3 342820362248886784 satisfy the kinematic and photometric criteria for membership but have RUWE > 1.6. For each star, the proper motion and parallax measurements are similar between DR2 and DR3 (and the first data release for THOR 10), which suggests that their astrometry may be reliable. The proper motion and parallax of THOR 8A are also similar to those of its candidate companion, THOR 8B, which is among the candidate members from the previous section. In addition, the six stars exhibit spectroscopic evidence of youth (Oppenheimer et al. 1997; Bell et al. 2017; Stauffer et al. 2020; this work). Therefore, I have adopted them as candidate members.

I searched for companions to the candidates from the previous section that are in Gaia DR3 but did not satisfy all of the selection criteria. To do that, I retrieved sources from DR3 that are located within 5″ from the candidates and that (1) fail the kinematic criteria but satisfy the photometric criteria and share roughly similar parallaxes and proper motions to their neighboring candidates or (2) satisfy the kinematic criteria but lack the photometry for the CMDs. The resulting candidate companions consist of 118 Tau Ba, THOR 9B, THOR 14Ab, HD 245924 B, RXJ0416.0+3325 B, and sources 241638674007806336, 3416960501912034816, 3237714611659033728, and 44866400900149248 from Gaia DR3.

Burgasser et al. (2016) identified the young L dwarf WISE J052857.68+090104.4 (Thompson et al. 2013) as a possible member of 32 Ori based on its proper motion, radial velocity, and a rough estimate of its distance that was derived from photometry. Since it does not appear in Gaia DR3 and lacks a parallax measurement, I am unable to assess its membership with the same level of scrutiny as the candidates selected in this work. As a result, it has been omitted from my census of 32 Ori.

2.4. Completeness and Contamination

The source catalog from Gaia DR3 has a high level of completeness at $G \lesssim 19–20$ for most of the sky (Boubert & Everall 2020; Fabricius et al. 2021), which corresponds to spectral types earlier than M7–M8 in 32 Ori. I have calculated the fraction of DR3 sources in my survey field that satisfy the following criteria utilized in my selection of candidates: $\sigma_{\mu} < 1$ mas, RUWE < 1.6, and $\sigma_{BP} < 0.1 / \sigma_{RP} < 0.1$ or $\sigma_{BP} < 0.1 / \sigma_{RP} < 0.1$. The resulting fraction varies from $\sim 80\%$ at $G = 5$ to $\sim 95\%$ at $G = 19$ and quickly declines at $G \gtrsim 19.5$. Thus, my census of 32 Ori should be $\sim 90\%$ complete for spectral types of $\lesssim M7$ and for the ranges of celestial coordinates and distance that have been considered.

I have estimated the field star contamination among the candidate members of 32 Ori by repeating the kinematic and photometric selection procedures with the $\Delta \mu_{x,y,z}$ criteria shifted by (+10,+10), (+10,−10), (0,+10), (0,−10), (−10,+10), (−10,0), and (−10,−10) mas yr$^{-1}$. On average, these eight samples contain five A/F/G stars, four M3–M6 stars, and five stars later than M6, which correspond to $\sim 9\%$ of the 158 stars that satisfy kinematic and photometric criteria for membership in 32 Ori. These results are roughly consistent with the number of candidates that are rejected via their $UVW$ velocities in Section 4. Those velocities are available for 69% of the 32 Ori candidates and lead to the rejection of three F/G/K stars and three M stars.

3. Spectroscopy of Candidates

I have used new and archival spectra of some of the candidate members of 32 Ori from Section 2 to measure their spectral types and radial velocities. The telescopes, instruments, and observing modes are summarized in Table 1, and
the measured classifications and velocities are provided in Table 2.

3.1. Spectral Classifications

To measure spectral types, I obtained IR spectra with SpeX (Rayner et al. 2003) at the NASA Infrared Telescope Facility (IRTF) on the nights of 2020 January 1, 20, and 21 and collected optical spectra with the Cerro Tololo Ohio State Multi-Object Spectrograph (COSMOS)\(^3\) at the 4 m Blanco telescope at the Cerro Tololo Inter-American Observatory (CTIO) on the night of 2021 January 2. In addition, I made use of the following archival data: an optical spectrum taken with the RC spectrograph at the CTIO 1.5 m telescope on the night of 2011 December 18 through program UR11b-10 (E. Mamajek), an IR spectrum taken with the IRTF/SpeX on the night of 2017 December 26 through program 2017B083 (Z. Zhang), and optical spectra from the seventh data release of the Large Sky Area Multi-Object Fiber Spectroscopic Telescope survey (LAMOST; Cui et al. 2012; Zhao et al. 2012).

The IRTF/SpeX data were reduced with the Spextool package (Cushing et al. 2004), which included correction of

\(^3\) COSMOS is based on an instrument described by Martini et al. (2011).
telluric absorption (Vacca et al. 2003). The optical spectra from CTIO were reduced with routines within IRAF. Examples of the reduced IR spectra are presented in Figure 5. The reduced optical and IR spectra are available in an electronic file associated with Figure 5.

Spectral classifications were performed for 96 objects, some of which were classified with data from multiple spectrographs. I assessed the ages of the targets using Li absorption at 6707 Å and gravity-sensitive features like the Na doublet near 8190 Å and the near-IR H2O absorption bands. The resolution of the LAMOST data is too low for the reliable measurement of weak Li absorption (Wλ ≈ 0.3 Å). For all targets, the spectra are consistent with the age of 32 Ori, although the available data are insufficient to distinguish between young stars and field dwarfs for spectral types near M2–M3, where Li is expected to be depleted in 32 Ori members (Bell et al. 2017) and the available gravity-sensitive features exhibit only subtle changes with age. Most of those stars do have measurements of radial velocities that support their membership (Section 4).

Spectral types were measured from the optical spectra through comparison to field dwarf standards for <M5 (Henry et al. 1994; Kirkpatrick et al. 1991, 1997) and averages of dwarf and giant standards for ≥M5 (Luhman et al. 1997; Luhman 1999). The IR spectra were classified with standard spectra derived from optically classified young sources (Luhman et al. 2017). Among the 96 sources for which spectral types were measured, 62 have been classified for the first time in this work. Spectral classifications remain unavailable for 26 of the candidates from Section 2, six of which have separations of ≤1″ from other stars.

3.2. Radial Velocities

I obtained high-resolution IR spectra of 39 candidate members of 32 Ori using iSHELL at the IRTF (Rayner et al. 2022). The selected observing mode for iSHELL (Table 1) produced spectra in orders 238–211, which span wavelengths from 2.17 to 2.46 μm. At least five exposures were collected for each target, most of which had exposure times of 3–5 minutes. The spectra were reduced using a version of Spextool (5.0.3) that was modified for use with iSHELL. The data were corrected for telluric absorption using the beta version of the IDL routine xtellcor._model.4

To measure radial velocities from the iSHELL data, I employed orders 226–217 (2.285–2.391 μm) because they encompassed a large number of strong photospheric absorption lines and relatively few saturated telluric lines. For each target, a template for its photospheric spectrum was derived from the iSHELL data with the Python package pychell (Cale et al. 2019), where the template was initialized with a BT-Settl model spectrum near the temperature and surface gravity of the target (Allard et al. 2012; Baraffe et al. 2015). For each order, a radial velocity was calculated by combining the barycentric correction (Wright & Eastman 2014) and the velocity shifts produced by cross-correlating the following pairs of spectra:

4 http://irtfweb.ifa.hawaii.edu/research/dr_resources/
the BT-Settl spectrum and the template, the template and the telluric-corrected target spectrum, and the uncorrected target spectrum and the model of telluric absorption utilized by xtellcor
\cite{Villanueva2018}. By including the latter cross-correlation, the telluric lines served as the source of the velocity calibration. The cross-correlations were performed with fxcor within IRAF \cite{Tonry1979}. The mean and standard deviation of the radial velocities from the 10 orders for each target are presented in Table 2. The median of the standard deviations is 1.0 km s\(^{-1}\).

### Table 2

| Column Label | Description |
|--------------|-------------|
| Gaia         | Gaia DR3 source name |
| RAdeg        | Gaia DR3 R.A. (ICRS at Epoch 2016.0) |
| DEdeg        | Gaia DR3 decl. (ICRS at Epoch 2016.0) |
| SpType       | Spectral type\(^a\) |
| Instrument   | Instrument used for spectral classification |
| RVel         | Barycentric radial velocity measured with iSHELL |
| e_RVel       | Error in RVel |

Note.\(^a\) Uncertainties are 0.25 and 0.5 subclass for optical and IR spectral types, respectively, unless indicated otherwise.

(316x187) (The data used to create this figure are available.)

### 4. Refining Candidates with UVW Velocities

For the candidate members of 32 Ori that have radial velocity measurements, their membership can be further constrained with UVW velocities. I have compiled radial velocities that have errors less than 4 km s\(^{-1}\) from this work and previous studies for 113 of the 175 candidates from Section 2. As done by Bell et al. (2017), I have excluded the available measurement for HD 35656 because it may be unreliable. Multiple velocities spanning a large range have been measured for HD 28693 \cite{Jonsson2020;AbdurroKuf2022;GaiaDR3}, THOR 31 \cite{Bell2017;GaiaDR3}, and RX J0437.4 +1851 B \cite{Wichmann2000;GaiaDR2}, so I have not adopted velocities for them. These stars may be spectroscopic binaries, in which case their system velocities will need to be characterized for the kind of analysis in this section. Some of the adopted radial velocities are from the APOGEE-2 program within the Sloan Digital Sky Survey IV \cite{SDSS-IV;Blanton2017;Majewski2017;AbdurroKuf2022}. The errors in those velocities are likely underestimated \cite{Cottaar2014;Tsantaki2022}. For each of two stars (V924 Tau A and B), I have adopted the median of the radial velocities measured at multiple epochs by the LAMOST Medium-resolution Survey as calibrated by Zhang et al. (2021), and I have adopted the standard deviation of the multiple measurements as the error.

The Astronomical Journal, 164:151 (19pp), 2022 October Luhman

Figure 5. Examples of spectra of candidate members of the 32 Ori association, which are displayed at a resolution of \(R = 150\). (The data used to create this figure are available.)

I have used the compiled radial velocities in conjunction with proper motions from Gaia DR3 and parallactic distances based on DR3 parallaxes \cite{Baier-Jones2021} to calculate UVW velocities \cite{Johnson1987}. The velocity errors were estimated in the manner described by Luhman & Esplin \cite{Luhman2020}. For most stars, the errors in \(U\) are larger than the errors in the other two velocity components because they are determined primarily by the radial velocity errors, which are usually larger than the equivalent errors in proper motion.
Before analyzing the available $UVW$ velocities for the 32 Ori candidates, I examine the spatial distribution of the full sample of 175 candidates from Section 2. I have plotted the $XYZ$ positions in Galactic Cartesian coordinates for all candidates in the top row of Figure 6. In addition, the candidates are shown on a map of equatorial coordinates in the right panel of Figure 2. In those diagrams, the candidates exhibit two subclusters and a sparser distribution of stars that extends primarily to higher values of $Y$. As shown in Figure 2, the 32 Ori candidates from Bell et al. (2017) are concentrated near one subcluster, while the 118 Tau candidates from Mamajek (2016) are located in the other subcluster. The $XYZ$ positions of the candidates that have measurements of radial velocities (and hence $UVW$ velocities) are plotted in the middle row of Figure 6. Those candidates provide a good sampling of the full list of candidates.

In the bottom row of Figure 6, the available measurements of $U$, $V$, and $W$ are plotted versus $X$, $Y$, and $Z$, respectively. Most of the velocities are tightly clustered in these diagrams, and each velocity component exhibits a positive correlation with spatial position except for $W$ at $Z \lesssim -20$ pc, which is roughly flat. These characteristics indicate that most of the candidates are members of a single association that is expanding.

I have rejected six candidates based on their discrepant velocities. Their names and velocities are provided in Table 3. These rejected stars are marked with crosses in Figure 6. Some of the measurements are beyond the limits of those diagrams. The velocity of one star, HD 281691, is only modestly discrepant, but it and a $7''$ companion both appear slightly below the sequence for 32 Ori in CMDs, which further indicates that they are probably not members. Although HD 281691 was selected as a candidate member of 32 Ori in Section 2, its companion was not among the candidates because it did not satisfy the kinematic selection criteria (the two stars straddle the thresholds).

Five additional candidates have $UVW$ velocities that are modestly discrepant: THOR 30, THOR 9A, HD245924 A, Gaia DR3 3411342134934571520, and HHJ 339. The discrepant
measurements are labeled with the source names in Figure 6. Only the first six digits of the Gaia designation are indicated. Two of the candidates, THOR 9A and HD245924 A, have subsarsecond companions that are resolved by Gaia, so their discrepant measurements could be due to astrometric errors caused by their companions. These five stars are retained in my catalog of candidates, but I consider their membership to be tentative.

For the 107 candidates that have measurements of $UVW$ velocities and that are retained in my final catalog, the median velocity is $U, V, W = -12.9, -18.9, -8.9$ km s$^{-1}$, which is similar to the value from Bell et al. (2017).

Among the 175 candidates from Section 2, six have been rejected in this section. The remaining 169 candidates are presented in Table 4, which includes source names from Gaia DR3, the 2MASS Point Source Catalog, the AllWISE Source Catalog (Cutri et al. 2013; Wright et al. 2013), and previous studies; equatorial coordinates, proper motion, parallax, RUWE, and photometric magnitudes from Gaia DR3; measurements of spectral types and the type adopted in this work; distance estimate based on Gaia DR3 parallax (Bailer-Jones et al. 2021); the most accurate available radial velocity measurement that has an error less than 4 km s$^{-1}$; the $UVW$ velocities calculated in this section; photometry from 2MASS and WISE; and flags indicating whether excesses are detected in three WISE bands and a disk classification if excess emission is detected (Section 6.4). If a source from 2MASS or WISE is resolved as a pair of candidates by Gaia, the former is matched only to the component that is brighter in Gaia photometry. 118 Tau A and B are not resolved in the AllWISE Source Catalog, but they are resolved in the WISE All-Sky Source Catalog (Cutri et al. 2012b), so the data from the latter have been adopted for the components of that system.

### Table 3

| Gaia DR3 | Other Name | $U$ (km s$^{-1}$) | $V$ (km s$^{-1}$) | $W$ (km s$^{-1}$) |
|----------|------------|------------------|------------------|------------------|
| 327365914308145792 | HD 24900 | $-30.1 \pm 0.1$ | $-20.7 \pm 0.1$ | $-22.3 \pm 0.1$ |
| 225883054629988096 | HD 279481 | $-35.6 \pm 0.4$ | $-9.1 \pm 0.2$ | $-11.8 \pm 0.1$ |
| 338700169274562048 | ... | $-21.7 \pm 1.9$ | $-21.7 \pm 0.4$ | $-12.2 \pm 0.6$ |
| 237427342611382016 | ... | $-6.5 \pm 0.2$ | $-20.3 \pm 0.1$ | $-7.5 \pm 0.1$ |
| 3296359400790170880 | ... | $-22.0 \pm 0.2$ | $-20.0 \pm 0.1$ | $-11.52 \pm 0.02$ |
| 164088748804295168 | HD 281691 | $-12.61 \pm 0.03$ | $-18.93 \pm 0.04$ | $-6.67 \pm 0.02$ |

5. Comparison to Previous Surveys

Rodriguez et al. (2014) proposed that the components of the wide binary system LDS 5606 are members of the β Pic moving group based on age diagnostics and estimates of $UVW$ velocities. However, they are among the candidate members of 32 Ori selected in Section 2, and their $UVW$ velocities from Section 4 agree closely with the bulk of the 32 Ori candidates. In addition, the binary is located ~80 pc from the center of the β Pic group and ~30 pc from the nearest candidate members from Shkolnik et al. (2017), but it resides within the volume inhabited by my 32 Ori candidates.

Bell et al. (2017) suggested that the eclipsing binary 2MASS J05525572−0044266 (Drake et al. 2014) may be a member of 32 Ori based on the radial velocity of the system. Murphy et al. (2020) calculated a $UVW$ velocity for the binary by combining a new measurement of the systemic radial velocity with astrometry from Gaia DR2. Based on that velocity, they adopted the binary as a member of 32 Ori, assigning it the designation of THOR 42. However, MacDonald & Mullan (2021) found that the binary is older than the 32 Ori association when the physical parameters of its components were interpreted with evolutionary models that include magnetic effects. That study also closely compared the $UVW$ data for THOR 42 from Murphy et al. (2020) and the velocities for other proposed members of 32 Ori, concluding that the kinematics of THOR 42 may provide additional evidence of nonmembership. THOR 42 was not selected as a candidate member of 32 Ori in Section 2 because it is slightly beyond the decl. boundary of my survey and does not satisfy my kinematic criteria. To examine its membership in more detail, I have calculated a new $UVW$ velocity using astrometry from Gaia DR3 and the radial velocity from Murphy et al. (2020), arriving at $(U, V, W) = (-15.9 \pm 0.4, -20.9 \pm 0.2, -5.4 \pm 0.1)$ km s$^{-1}$. Given its XYZ position of (−89.8, −45.4, −23.9) pc, the system’s $U$ and $V$ measurements are consistent with membership (although it would be a spatial outlier in $Y$), but the $W$ velocity exhibits a fairly large discrepancy (~4 km s$^{-1}$) relative to the other candidates in my catalog (see Figure 6). Thus, this kinematic analysis supports the suggestion from MacDonald & Mullan (2021) that THOR 42 is not a member of 32 Ori.

Gagné & Faherty (2018) used data from Gaia DR2 to search for new candidates for members of several nearby associations, including 118 Tau and 32 Ori. They identified nine candidates for either of the groups, eight of which are among my candidates for 32 Ori. The one remaining candidate does not satisfy the kinematic selection criteria from Section 2.1.

During analysis of $UVW$ velocities for previously identified members of several nearby associations, Lee & Song (2019) proposed the existence of a single group that combines members of 32 Ori and a subset of members of the Columba association. Their new group contained 49 stars, 41 of which were originally identified as Columba members. The data in Table 3 illustrate that those two subsets of stars do not share similar kinematics and hence do not represent a single association. 2MASS J04435686+3723033 and 2MASS J04435750+3723031 likely comprise a wide binary system (Schlieder et al. 2010; Phillips et al. 2020). Some studies have proposed that the system is a member of the β Pic moving group (Schlieder et al. 2010; Malo et al. 2014; Shkolnik et al. 2017), while others have found that its membership in that association is uncertain (Messina et al. 2017; Phillips et al. 2020). Both
Table 4
Candidate Members of 32 Ori from Gaia DR3

| Column Label | Description |
|--------------|-------------|
| Gaia         | Gaia DR3 source name |
| 2MASS        | 2MASS source name |
| WISEA        | AllWISE source name |
| Name         | Other source name |
| RAdeg        | Gaia DR3 R.A. (ICRS at Epoch 2016.0) |
| DEdeg        | Gaia DR3 decl. (ICRS at Epoch 2016.0) |
| SpType       | Spectral type |
| e_SpType     | Spectral type referencea |
| Adopt        | Adopted spectral type |
| pmRA         | Gaia DR3 proper motion in R.A. |
| e_pmRA       | Error in pmRA |
| pmDec        | Gaia DR3 proper motion in decl. |
| e_pmDec      | Error in pmDec |
|plx           | Gaia DR3 parallax |
| e_plx        | Error in plx |
| rhigeo       | Median of geometric distance posterior (Bailer-Jones et al. 2021) |
| rlogeo       | 84th percentile of geometric distance posterior (Bailer-Jones et al. 2021) |
| rmedgeo      | 16th percentile of geometric distance posterior (Bailer-Jones et al. 2021) |
| Notes.       | 84th percentile of geometric distance posterior (Bailer-Jones et al. 2021) |
| RVel         | Radial velocity |
| e_RVel       | Error in RVel |
| r_RVel       | Radial velocity referenceb |
| U            | U component of space velocity |
| e_U          | Error in U |
| V            | V component of space velocity |
| e_V          | Error in V |
| W            | W component of space velocity |
| e_W          | Error in W |
| Gmag         | Gaia DR3 G magnitude |
| e_Gmag       | Error in Gmag |
| GBPmag       | Gaia DR3 G.bp magnitude |
| e_GBPmag     | Error in GBPmag |
| GRPmag       | Gaia DR3 G.pr magnitude |
| e_GRPmag     | Error in GRPmag |
| RUWE         | Gaia DR3 renormalized unit weight error |
| 3mag         | 2MASS J magnitude |
| e_3mag       | Error in 3mag |
| Hmag         | 2MASS H magnitude |
| e_Hmag       | Error in Hmag |
| Kmag         | 2MASS K magnitude |
| e_Kmag       | Error in Kmag |
| W1mag        | WISE W1 magnitude |
| e_W1mag      | Error in W1mag |
| f_W1mag      | Flag on W1mag |
| W2mag        | WISE W2 magnitude |
| e_W2mag      | Error in W2mag |
| f_W2mag      | Flag on W2mag |
| W3mag        | WISE W3 magnitude |
| e_W3mag      | Error in W3mag |
| f_W3mag      | Flag on W3mag |
| W4mag        | WISE W4 magnitude |
| e_W4mag      | Error in W4mag |
| f_W4mag      | Flag on W4mag |
| ExcW2        | Excess present in W2? |
| ExcW3        | Excess present in W3? |
| ExcW4        | Excess present in W4? |
| DiskType     | Disk type |

Notes.

a (1) this work; (2) Aberasturi et al. 2014; (3) Birky et al. 2020; (4) Oppenheimer et al. 1997; (5) Cannon & Pickering 1993; (6) Wichmann et al. 1996; (7) Findeisen & Hillenbrand 2010; (8) Nguyen et al. 2012; (9) Kraus et al. 2017; (10) Schlieder et al. 2012a; (11) Slesnick et al. 2006; (12) Schlieder et al. 2010; (13) Malo et al. 2014; (14) Fouqué et al. 2018; (15) Bowler et al. 2019; (16) Phillips et al. 2020; (17) Rodríguez et al. 2014; (18) Li & Hu 1998; (19) Esplin & Luhman 2019; (20) Bell et al. 2017; (21) Herczeg & Hillenbrand 2014; (22) Alcalá et al. 1996; (23) Alcalá et al. 2000; (24) Biazzo et al. 2012; (25) Liu et al. 2021; (26) Gagné et al. 2015b; (27) Houk & Swift 1999; (28) Cowley et al. 1969; (29) Abt & Morrell 1995; (30) Grenier et al. 1999; (31) Abt 2008; (32) Suárez et al. 2017; (33) Briceño et al. 2019; (34) Abt & Levato 1977; (35) Edwards 1976; (36) Binks et al. 2015; (37) Abt 2004.

b (1) Gaia DR3; (2) Abdurro’uf et al. 2022; (3) Nguyen et al. 2012; (4) Zhang et al. 2021 and LAMOST DR7; (5) this work; (6) Kraus et al. 2017; (7) Fouqué et al. 2018; (8) Phillips et al. 2020; (9) Rodríguez et al. 2014; (10) Bell et al. 2017; (11) Zúñiga-Fernández et al. 2021; (12) Alcalá et al. 2000; (13) Gontcharov 2006; (14) Grenier et al. 1999; (15) White et al. 2007; (16) Soubiran et al. 2018.

c ndet = nondetection; false = detection from AllWISE appears to be false or unreliable based on visual inspection.

(This table is available in its entirety in machine-readable form.)
components of the pair are among the candidate members of 32 Ori selected in Section 2, and my calculations for their $U/V/W$ velocities in Section 4 agree well with velocities of other 32 Ori candidates when the expansion pattern of the association is taken into account, as shown in Figure 6. For reference, the binary has an $XYZ$ position of $(-68.8, 17.6, -6.9)$ pc and a $U/V/W$ velocity near $(-11, -19, -8)$ km s$^{-1}$ (Table 4). The system is located near the edge of the 32 Ori association in $XYZ$, but it is not an outlier.

Stauffer et al. (2020) proposed that HHJ 339 and HHJ 430 are members of the 32 Ori association based on their evidence of youth and the available constraints on their kinematics, primarily from Gaia DR2. Both stars are among the candidates selected in Section 2, so my analysis supports the results from Stauffer et al. (2020). The $U$ velocity of HHJ 339 is modestly discrepant, as shown in Figure 6, but it is retained in my catalog of candidates (Section 4).

Liu et al. (2021) used data from Gaia DR2 to identify young groups within a volume of space that overlaps with the volume considered in my survey for 32 Ori. My sample of candidates for 32 Ori contains 32 stars that appear in group 11 from Liu et al. (2021). That group includes one additional star (Gaia DR3 3427527766435285248) that is absent from my catalog because it exceeds my adopted threshold for RUWE.

Kerr et al. (2021) used data from Gaia DR2 to identify groups of young stars within a distance of a few hundred parsecs. Two of their groups, GT6 and GT7, overlap with my catalog of candidates for 32 Ori. For each group, Kerr et al. (2021) presented a core sample and an expanded sample in which contamination by nonmembers was expected to be higher. The core/expanded samples for GT6 included 4/10 of the 11 members of 118 Tau from Mamajek (2016), while the core/expanded samples for GT7 contained 7/17 of the 44 members of 32 Ori from Bell et al. (2017) that have Gaia DR3 parallaxes. The total numbers of candidates in their core/expanded samples were 33/98 for GT6 and 11/25 for GT7; 31/50 of the stars in GT6 and all of the stars in the two samples for GT7 appear in my catalog for 32 Ori. Among the GT6 candidates from Kerr et al. (2021) that are absent from my sample of candidates, four are outside of the field that I have considered, one satisfies all of my selection criteria except for RUWE, and the remaining stars are rejected based on their photometry or kinematics.

Kraus et al. (2017) suggested that the originally proposed members of 118 Tau and 32 Ori might be kinematically related to the Taurus star-forming region. Based on the kinematic data for my sample of 32 Ori candidates (Section 4) and the kinematics of known members of Taurus (Luhman 2018), the median $U/V/W$ velocity of the 32 Ori association differs by $>5$ km s$^{-1}$ from the median velocities of the stellar aggregates in Taurus, which demonstrates that the 32 Ori candidates did not originate from the Taurus clouds. Meanwhile, if the $XYZ$ positions of the 32 Ori association and the Taurus aggregates are traced back in time using their median velocities (Section 6.2), 32 Ori was never closer than $\sim$15 pc from any of the Taurus aggregates. These kinematic and spatial separations between 32 Ori and Taurus are common among young associations in the solar neighborhood (Bell et al. 2017; Gagné et al. 2018c), so there is no evidence that 32 Ori and Taurus have any meaningful relationship. The same has been found for other associations that are in the vicinity of Taurus but are kinematically distinct from it (Luhman 2018; Gagné et al. 2020).

6. Properties of the 32 Ori Stellar Population

6.1. Initial Mass Function

As in my previous studies of young clusters and associations, I have used spectral type as an observational proxy for stellar mass when characterizing the IMF of the 32 Ori association. For 32 Ori candidates that lack spectral classifications and have the necessary photometry, I have estimated spectral types from a comparison of $G_{BP} - G_{RP}$, $G_{BP} - J$, $J - H$, and $H - K_s$ to the intrinsic values expected for young stars at various spectral types (Luhman 2022a). Three candidates lack measurements of spectral types and colors, consisting of THOR 14Ab, THOR 9B, and HD 245924 B. Gaia DR3 provides a measurement of $G$ for the former but contains no photometry for the latter two stars. I have adopted $K$-band data for THOR 9B from Baldwin-Saavedra et al. (2009) and $V$-band data for HD 245924 B from Mason et al. (2001). The spectral types of those three stars were estimated by combining their absolute magnitudes in those bands with the average relations between those magnitudes and spectral type for other 32 Ori candidates.
$G_{RP} - J$, $J - H$, and $H - K_s$ for the 32 Ori candidates are plotted in Figure 8 with the typical intrinsic colors of young stars. Those data demonstrate that the candidates have little extinction ($A_K \approx 0.04$; see also Bell et al. 2017), so I have assumed that all candidates have no extinction when estimating their spectral types from colors. RX J0437.4+1851 A and B and Gaia DR3 3241254244532020608, 3416550830753546368, and 241638674007806336 have discrepant near-IR colors, all of which are blended with companions or field stars. Those colors are likely erroneous because of the blending, so they have been omitted from Figure 8.

In Figure 9, I have plotted a histogram of spectral types for candidate members of the 32 Ori association from Table 4. For stars that lack spectroscopy, spectral types have been estimated from photometry (Figure 8).

In Figure 9, I have plotted a histogram of spectral types for the 32 Ori candidates. As discussed in Section 2.4, this sample should have a high level of completeness for spectral types earlier than $\sim$M7, which corresponds to masses of $\gtrsim 0.06 M_\odot$ for an age of $\sim$20 Myr (Baraffe et al. 1998, 2015). The histogram exhibits a maximum near M5 ($\sim 0.15 M_\odot$) and thus closely resembles the distributions measured for other young clusters and associations in the solar neighborhood (e.g., Luhman 2022a).

6.2. Kinematic Ages

Two kinds of kinematic ages are often investigated for unbound associations of young stars, consisting of the expansion age and the traceback age (Blaauw 1964; Brown et al. 1997; Ducourant et al. 2014; Mamajek & Bell 2014; Goldman et al. 2018; Zari et al. 2019; Crundall et al. 2019; Miret-Roig et al. 2020; Swiggum et al. 2021). I have attempted to constrain these ages for the 32 Ori association using the
candidates in my catalog that have measurements of $UVW$ velocities. The six modest kinematic outliers that are labeled in Figure 6 and discussed in Section 4 are omitted from this analysis.

As discussed in Section 4 and illustrated in Figure 6, the space velocities for the 32 Ori candidates exhibit correlations with spatial positions that indicate the presence of expansion. I have estimated the slopes of these correlations using robust linear regression with bootstrap sampling, arriving at have estimated the slopes of these correlations using robust linear regression with bootstrap sampling, arriving at $\pm 0.050 \sigma$.

Figure 11. $M_{G_{\text{BP}}}$ vs. $G_{\text{BP}} - G_{\text{RP}}$ and $G - G_{\text{RP}}$ for candidate members of the 32 Ori association from Table 4. The two stars that appear below the sequence in the left CMD are the disk-bearing stars mentioned in Section 2.2.

6.3. Isochronal Ages

By providing high-precision photometry and parallaxes, Gaia has enabled the accurate measurement of the sequences of young associations in CMDs. In Figure 11, I have plotted $M_{G_{\text{BP}}}$ versus $G_{\text{BP}} - G_{\text{RP}}$ and $G - G_{\text{RP}}$ for the candidate members of 32 Ori from Table 4. The sequences in those CMDs are narrow and well defined, so they can be used to constrain the age of 32 Ori relative to other associations. For that analysis, I consider stars with $G_{\text{BP}} - G_{\text{RP}} = 1.4 - 2.8$ (K5–M4), which should have masses of $\sim 0.2 - 1 M_{\odot}$ (Baraffe et al. 2015). Stars across that mass range are expected to exhibit similar evolution in their luminosities from $\sim 1$ to $30 \text{ Myr}$ (Herczeg & Hillenbrand 2015).

Luhman & Esplin (2020) used data from Gaia DR2 to compare the relative ages of Sco-Cen populations and other young associations, including 32 Ori. They found that the sequence of low-mass stars in 32 Ori (Bell et al. 2017) is $0.12 \pm 0.06 \text{ mag}$ brighter than that of the $\beta$Pic moving group (Bell et al. 2015; Gagné & Faherty 2018), which implied that the former is younger by $\sim 3$ Myr according to evolutionary models (Baraffe et al. 2015; Choi et al. 2016; Dotter 2016; Feiden 2016). Binks & Jeffries (2016) estimated ages of $21/24 \pm 4 \text{ Myr}$ for $\beta$Pic from the lithium depletion boundary using nonmagnetic/magnetic models. UCL/LCC was brighter than $\beta$Pic by $0.10 \pm 0.02 \text{ mag}$, indicating that 32 Ori and UCL/LCC have similar ages.

I have updated the previous comparison of 32 Ori, $\beta$Pic, and UCL/LCC to use data from Gaia DR3 and the new samples of candidates in 32 Ori and UCL/LCC from Table 4 and Luhman (2022a), respectively. For each association, I consider stars that have $G_{\text{BP}} - G_{\text{RP}} = 1.4 - 2.8$, $\sigma_{\text{BP}} < 0.1 \text{ mas}$, $\text{RUWE} < 1.6$, $\sigma_{G_{\text{BP}}} < 0.1$, and $\sigma_{G_{\text{RP}}} < 0.1$. Stars that have full disks are excluded because accretion-related emission can contaminate the Gaia colors (Section 6.4; Luhman 2022b). The miscellaneous candidates in 32 Ori from Section 2.3 are also omitted since...
some of their parallactic distances may not be reliable. The sample for UCL/LCC is defined with the criteria on kinematics and celestial coordinates that were utilized by Luhman (2022b). For each star in the three associations, I have calculated the difference between their median \( \Delta M_{\text{GRP}} \) offsets and have estimated the error in that difference using the median absolute deviations (MADs) for the distribution of differences produced by bootstrapping. 32 Ori and UCL/LCC are brighter than \( \beta \) Pic by \( 0.13 \pm 0.06 \) mag and \( 0.12 \pm 0.04 \) mag, respectively, and 32 Ori and UCL/LCC differ by \( 0.00 \pm 0.04 \) mag. These measurements are similar to the values from Luhman & Esplin (2020), so the age estimates from that study remain valid. The difference of \( 0.00 \pm 0.04 \) mag for 32 Ori and UCL/LCC indicates that they are coeval to within \( \pm 1.2 \) Myr according to evolutionary models.

As mentioned in Section 5, groups GT6 and GT7 from Kerr et al. (2021) correspond to subsets of previously proposed members of 118 Tau and 32 Ori, respectively. That study reported significantly different ages of 16.8 \( \pm 2.0 \) Myr and 27.2 \( \pm 3.8 \) Myr for those groups, respectively. To examine the relative ages of the subclusters, I have selected two samples of 32 Ori candidates from the preceding age analysis, one with \( \alpha > 75^\circ \) and \( \delta < 18^\circ \) (the 32 Ori subcluster) and one with \( \alpha > 75^\circ \) and \( \delta > 18^\circ \) (the 118 Tau subcluster), each of which contains 12 stars. The 118 Tau sample is brighter by 0.13 \( \pm 0.10 \) mag, which should correspond to an age that is younger by \( \sim 3.6 \pm 2.9 \) Myr based on evolutionary models. This age difference is smaller than that found by Kerr et al. (2021) and has marginal significance.

### 6.4. Circumstellar Disks

I have used mid-IR photometry from WISE to check for evidence of circumstellar disks around the candidate members of 32 Ori. The images from WISE were obtained in bands centered at 3.4, 4.6, 12, and 22 \( \mu \)m, which are denoted as W1, W2, W3, and W4, respectively. The angular resolution of Gaia DR3 is more than an order of magnitude higher than that of the WISE images (Wright et al. 2010; Fabricius et al. 2021), so a close pair of 32 Ori candidates can appear as a single unresolved source in WISE. For each pair of this kind, the WISE source has been matched to the brighter component in Gaia, as mentioned in Section 4. For the 169 candidates in Table 4, I have identified 160 matching sources in WISE. I have visually inspected the AllWISE Atlas images of all of the WISE sources to check for detections that are false or unreliable, which are indicated by a flag in Table 4. The measurements for false detections have been omitted from Table 4 and are not used in this work.

As done in the disk survey by Luhman (2022a), I have used W1−W2, W1−W3, and W1−W4 to detect excess emission from disks. In Figure 13, I have plotted those colors versus spectral type for the WISE sources from Table 4. The W2 data at W2 < 6 have been omitted since they are subject to significant systematic errors (Cutri et al. 2012a). For stars that lack spectroscopic measurements of spectral types, I have adopted the photometric estimates from Section 6.1. In each of the three colors in Figure 13, most stars are found in a well-defined sequence that corresponds to stellar photospheres. A smaller number of stars are redder than that sequence, indicating the presence of IR excess emission. In each diagram in Figure 13, I have marked the threshold that was used by...
Luhman (2022b) for identifying color excesses. If a star appears above a given threshold but a detection in any band at a longer wavelength is consistent with a photosphere, an excess is not assigned to the first band. In Table 4, I have included three flags that indicate whether excesses are identified in W2, W3, and W4. Flags are absent for nondetections.

For each source that has IR excess emission, I have classified the evolutionary stage of its disk from among the following options: full disk, transitional disk, evolved disk, evolved transitional disk, and debris disk (Kenyon & Bromley 2005; Rieke et al. 2005; Hernández et al. 2007; Luhman et al. 2010; Espaillat et al. 2012). All of these classes except for the last are considered primordial disks. I have assigned these disk classes based on the sizes of the excesses in \( K_s - W3 \) and \( K_s - W4 \) in the manner done in my previous disk surveys with WISE (Luhman & Mamajek 2012; Esplin et al. 2014, 2018). The color excesses, \( E(K_s - W3) \) and \( E(K_s - W4) \), are calculated by subtracting the expected photospheric color for a given spectral type (Luhman 2022a). The resulting excesses are plotted in Figure 14 with the criteria for the disk classes (Esplin et al. 2018). The excesses in \( K_s - W2 \) have been included as well to illustrate the sizes of the excesses in W2. As indicated in the diagram containing \( E(K_s - W3) \) and \( E(K_s - W4) \), the same criteria are used for debris and evolved transitional disks, which are indistinguishable in mid-IR data. Sources that lack excesses in any of the WISE bands are omitted from Figure 14 and are designated as class III (Lada & Wilking 1984; Lada 1987). The sizes of the excesses for HD 36546 are indicative of a
transitional disk according to my adopted classification criteria, but I have labeled it as a debris disk based on more detailed observations from previous studies (McDonald et al. 2012; Wu et al. 2013; Liu et al. 2014; Currie et al. 2017; Lisse et al. 2017). IR excesses from disks are detected for 18 of the 160 WISE sources. Nine of those disks have been identified in previous work (Herzeg & Hillenbrand 2008; McDonald et al. 2012; Shvonski et al. 2016; Bell et al. 2017; Liu et al. 2021). The 18 disks consist of 12 full, 1 transitional, 4 debris or evolved transitional, and 1 debris. The coolest disk-bearing sources are Gaia DR3 332033517521540864 and 3237866752286153088, which have spectral types of M8 and M9, corresponding to masses of $\sim0.04$ and $0.02 M_\odot$ (Luhman et al. 2003; Baraffe et al. 2015). Bell et al. (2017) reported W4 excesses for THOR 4B and THOR 38, but I have classified those W4 detections as false or unreliable.

Among WISE sources in 32 Ori that have spectral types of $\leq M6$, the fraction that have full, transitional, or evolved disks is 10/149 = 0.07$^{+0.03}_{-0.02}$. That value is consistent with the disk fraction for the same range of types in UCL/LCC (0.067$^{+0.004}_{-0.005}$, Luhman 2022b), which has a similar age to 32 Ori (Section 6.3).

### 7. Conclusions

I have performed a survey for members of the 32 Ori association using high-precision photometry and astrometry from Gaia DR3 and ground-based spectroscopy. The new catalog of candidate members has been used to characterize the IMF and age of the association and to identify and classify its circumstellar disks. The results are summarized as follows:

1. I have defined kinematic and photometric criteria for selecting candidate members of 32 Ori using data from Gaia DR3 for previously proposed members (Mamajek 2007; Bell et al. 2017) and stars associated with 118 Tau (Mamajek 2016), which are spatially adjacent to the 32 Ori members and share similar space motions. I have applied the selection criteria to sources from Gaia DR3 that have $\alpha = 50^\circ$–$90^\circ$, $\delta = 0^\circ$–$45^\circ$, and distances of 70–120 pc. The resulting sample contains 158 candidates, which includes previously proposed members. I also have assigned candidacy to 17 additional stars from Gaia DR3 that do not satisfy the selection criteria but that have other evidence suggestive of membership (e.g., close companion to a candidate).

2. I have used new and archival spectra to measure spectral types for 96 candidates, 62 of which have been classified for the first time in this work. All of the age diagnostics in these spectra are consistent with the youth expected for membership in 32 Ori, although some candidates lack the necessary data for discrimination between young stars and field dwarfs. In addition, I have obtained high-resolution IR spectra of 39 candidates to measure their radial velocities.

3. I have calculated $UVW$ velocities for 113 of the 175 candidates that have measurements of radial velocities. In diagrams of $U/V/W$ versus $X/Y/Z$, most of the candidates are well clustered and exhibit positive correlations, which indicates that they comprise a single association that is expanding. Six candidates are rejected based on discrepant $UVW$ velocities and other data, leaving 169 candidates in the final catalog. The spatial distribution of the candidates shows two subclusters centered near the stars 32 Ori and 118 Tau, which is where most of the candidates from Bell et al. (2017) and Mamajek (2016) are located.

4. The new catalog of candidates for 32 Ori should have a high level of completeness ($\sim 90\%$) for spectral types of $\lesssim M7$ ($\gtrsim 0.06 M_\odot$) and for the ranges of celestial coordinates and distance that have been considered. Based on the selection criteria in this survey, I estimate that my catalog of candidates may include approximately eight field stars, likely consisting of a few A/F/G stars and several M stars. Additional spectroscopy to measure spectral types, age diagnostics, and radial velocities for candidates that lack those data would help to reject such nonmembers.

5. The histogram of spectral types for the 32 Ori candidates exhibits a maximum at M5 ($\sim 0.15 M_\odot$), indicating an IMF that has a similar characteristic mass to other young clusters and associations in the solar neighborhood.

6. I have attempted to use the $UVW$ velocities that are available for the 32 Ori candidates to derive kinematic ages for the association based on the expansion rates in $X$, $Y$, and $Z$ and the traceback of XYZ positions to their smallest configuration in the past. Neither of these analyses produces a well-defined age.

7. I have constrained the relative ages of the 32 Ori association, the $\beta$ Pic moving group, and UCL/LCC in Sco-Cen using their sequences of low-mass stars in CMDs constructed from Gaia data. In terms of those sequences, 32 Ori and UCL/LCC are brighter than $\beta$ Pic by 0.13 ± 0.06 mag and 0.12 ± 0.04 mag, respectively, and 32 Ori and UCL/LCC differ by 0.00 ± 0.04 mag, indicating that 32 Ori and UCL/LCC are coeval to within $\pm 1.2$ Myr and are younger than $\beta$ Pic by $\sim 3$ Myr. These
results are consistent with analysis of Gaia DR2 data for previous samples of candidates in 32 Ori and UCL/LCC (Luhman & Esplin 2020). For reference, Binks & Jeffries (2016) estimated ages of 21/24 ± 4 Myr for β Pic from the lithium depletion boundary using nonmagnetic/magnetic models.

8. I have used mid-IR photometry from WISE to identify 32 Ori candidates that exhibit IR excesses from disks, and I have classified the evolutionary stages of the detected disks using the sizes of the excesses. Excesses are detected for 18 of the 160 WISE sources that are matched to the candidates from Gaia. Eight of these disks are reported for the first time in this work. Among candidates with spectral types of <M6, the fraction that have full, transitional, or evolved disks is 10/149 = 0.07±0.03, which is consistent with the value for UCL/LCC (0.067±0.005, Luhman 2022b).

I thank Bryson Cale, Peter Plavchan, and Adwin Boogert for assistance with the analysis of the ISHELL data. The IRTF is operated by the University of Hawaii under contract 80HQTR19D0030 with NASA. The observations at the CTIO 4-m Blanco telescope were performed through program 2020B-0049 at NOIRLab. This work used data provided by the Astro Data Archive at NOIRLab. CTIO and NOIRLab are operated by the Association of Universities for Research in Astronomy under a cooperative agreement with the NSF. This work used data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. 2MASS is a joint project of the University of Massachusetts and IPAC at Caltech, funded by NASA and the NSF. WISE is a joint project of the University of California, Los Angeles, and JPL/Caltech, funded by NASA. This work used data from the NASA/IPAC Infrared Science Archive, operated by JPL under contract with NASA, and the VizieR catalog access tool and the SIMBAD database, both operated at CDS, Strasbourg, France. Guoshoujing Telescope (the Large Sky Area Multi-Object Fiber Spectroscopic Telescope, LAMOST) is a National Major Scientific Project built by the Chinese Academy of Sciences. Funding for the project has been provided by the National Development and Reform Commission. LAMOST is operated and managed by the National Astronomical Observatories, Chinese Academy of Sciences. Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS-IV acknowledges support and resources from the Center for High Performance Computing at the University of Utah. The SDSS website is www.sdss.org. SDSS-IV is managed by the Astrophysical Research Consortium on behalf of the Participant Institutions of the SDSS Collaboration, including the Brazilian Participation Group, the Carnegie Institution for Science, Carnegie Mellon University, Center for Astrophysics—Harvard & Smithsonian, the Chilean Participation Group, the French Participation Group, Instituto de Astrofísica de Canarias, Johns Hopkins University, Kavli Institute for the Physics and Mathematics of the Universe (IPMU)/University of Tokyo, the Korean Participation Group, Lawrence Berkeley National Laboratory, Leibniz Institut für Astrophysik Potsdam (AIP), Max-Planck-Institut für Astronomie (MPIA Heidelberg), Max-Planck-Institut für Astrophysik (MPA Garching), Max-Planck-Institut für Extraterrestrische Physik (MPE), National Astronomical Observatories of China, New Mexico State University, New York University, University of Notre Dame, Observatório Nacional/MCTI, The Ohio State University, Pennsylvania State University, Shanghai Astronomical Observatory, United Kingdom Participation Group, Universidad Autónoma de México, University of Arizona, University of Colorado Boulder, University of Oxford, University of Portsmouth, University of Utah, University of Virginia, University of Washington, University of Wisconsin, Vanderbilt University, and Yale University. The Center for Exoplanets and Habitable Worlds is supported by the Pennsylvania State University, the Eberly College of Science, and the Pennsylvania Space Grant Consortium.

ORCID iDs

K. L. Luhman @ https://orcid.org/0000-0003-2822-2951

References

Abdurro’uf, Accetta, K., & Aerts, C. 2022, ApJS, 259, 35
Aberasturi, M, Caballero, J. A., Montesinos, B., et al. 2014, AJ, 148, 36
Ablt, H. A. 2004, ApJS, 155, 175
Ablt, H. A. 2008, ApJS, 176, 216
Ablt, H. A., & Levato, H. 1977, PASP, 89, 797
Abt, H. A., & Morell, N. I. 1995, ApJS, 99, 135
Alcalá, J. M., Covino, E., Torres, G., et al. 2000, A&A, 353, 186
Alcalá, J. M., Terranegra, L., Wichmann, R., et al. 1996, A&AS, 119, 7
Allard, F., Homeier, D., & Freytag, B. 2012, RSPTA, 370, 2765
Aller, K. M., Liu, M. C., Magnier, E. A., et al., 2016, ApJ, 821, 120
Bailey-Jones, C. A. L., Rybicki, J., Fousneau, M., Demleitner, M., & Andrae, R. 2021, AJ, 161, 147
Baldovini-Savordina, C., Audard, M., Duchêne, G., et al. 2009, ApJ, 697, 420
Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1995, A&A, 337, 403
Baraffe, I., Homeier, D., Allard, F., & Chabrier, G. 2015, A&A, 577, 42
Bardalez Gagliuffi, D. C., Gagné, J., Faherty, J. K., & Burgasser, A. J. 2018, ApJ, 854, 101
Bell, C. P. M., Mamajek, E. E., & Naylor, T. 2015, MNRAS, 454, 593
Bell, C. P. M., Murphy, S. J., & Mamajek, E. E. 2017, MNRAS, 468, 1198
Best, W. M. J., Liu, M. C., Dupuy, T. J., & Magnier, E. A. 2017, ApJL, 843, L4
Biazzo, K., Alcalá, J. M., Covino, E., et al. 2012, A&A, 542, A115
Binks, A. S., Chelliﬁour, M., Kastner, J. H., et al. 2020, MNRAS, 491, 215
Binks, A. S., & Jeffries, R. D. 2016, MNRAS, 455, 3345
Binks, A. S., Jeffries, R. D., & Maxted, P. F. L. 2015, MNRAS, 452, 173
Binks, A. S., Jeffries, R. D., & Ward, J. L. 2018, MNRAS, 473, 2465
Birky, J., Hogg, D. W., Mann, A. W., & Burgasser, A. 2020, ApJ, 892, 31
Blauw, A. 1964, ARAA, 2, 213
Blanton, M. R., Bershadly, M. A., Abolfathi, B., et al. 2017, AJ, 154, 28
Bouhert, D., & Everall, A. 2020, MNRAS, 497, 4246
Bowler, B. P., Hinkley, S., Ziegler, C., et al. 2019, ApJ, 877, 60
Briceno, C., Calvet, N., Hernández, J., et al. 2019, AJ, 157, 85
Brown, A. G. A., Dekker, G., & de Zeeuw, P. T. 1997, MNRAS, 285, 479
Burgasser, A. J., Lopez, M. A., Mamajek, E. E., et al. 2016, ApJ, 820, 32
Cale, B., Plavchan, P., LeBrun, D., et al. 2019, AJ, 158, 170
Cannon, A. J., & Pickering, E. C. 1993, VizieR On-line Data Catalog: III/135A
Choi, J., Dotter, A., Conroy, C., et al. 2016, ApJ, 823, 102
Cottaar, M., Covey, K. R., Meyer, M. R., et al. 2014, ApJ, 794, 125
Cowley, A., Cowley, C., Jaschek, M., & Jaschek, C. 1969, AJ, 74, 375
Cralland, T. D., Ireland, M. J., Krumholz, M. R., et al. 2019, MNRAS, 489, 3625
Cutri, R., et al. 2012, RAAS, 12, 1197
Currie, T., Guyon, O., Tamura, M., et al. 2017, ApJL, 836, L15
Cushing, M. C., Vacca, W. D., & Rayner, J. T. 2004, PASP, 116, 362
Cutri, R. M., Wright, E. L., Conrow, T., et al. 2012a, Explanatory Supplement to the WISE All-Sky Data Release Products
Cutri, R. M., Wright, E. L., Conrow, T., et al. 2012b, VizieR On-line Data Catalog: II/311
