Spectroscopy of Candidate Members of the Sco-Cen Complex

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Abstract

We present spectroscopy of 285 previously identified candidate members of populations in the Sco-Cen complex, primarily Ophiuchus, Upper Sco, and Lupus. The spectra are used to measure spectral types and diagnostics of youth. We find that 269 candidates exhibit signatures of youth in our spectra or previous data, which is consistent with their membership in Sco-Cen. We have constructed compilations of candidate members of Ophiuchus, Upper Sco, and Lupus that have spectral classifications and evidence of youth, which contain a total of 2274 objects. In addition, we have used spectra from previous studies to classify three sources in Ophiuchus that have been proposed to be protostellar brown dwarfs: ISO Oph 70, 200, and 203. We measure spectral types of early M from those data, which are earlier than expected for young brown dwarfs based on evolutionary models (\( \geq M_{6.5} \)) and instead are indicative of stellar masses (\( \sim 0.6 M_\odot \)).

Unified Astronomy Thesaurus concepts: Star formation (1569); Star forming regions (1565); Low mass stars (1553); OB associations (1140); Stellar associations (1582)

Supporting material: data behind figures, machine-readable tables

1. Introduction

Spectroscopic surveys in nearby star-forming regions are important for providing large samples of members that have measured spectral types and confirmation of youth, which can serve as the foundation for various studies of star and planet formation (Hillenbrand 1997). The populations within the Scorpius-Centaurus complex (Sco-Cen; Preibisch & Mamajek 2008) are appealing targets for such surveys because of their richness and proximity (100–200 pc; de Zeeuw et al. 1999). These populations consist of the stars associated with the Ophiuchus and Lupus clouds, a compact group surrounding the star V1062 Sco, Upper Scorpius, Upper Centaurus-Lupus (UCL), and Lower Centaurus-Crux (LCC), where the latter two are known to comprise a single continuous distribution of stars (Rizzuto et al. 2011; Luhman 2021a).

A variety of methods have been used to identify candidate members of Sco-Cen (Comerón 2008; Preibisch & Mamajek 2008; Wilking et al. 2008). Recent progress has been enabled by the high-precision astrometry from the Gaia mission (Perryman et al. 2001; de Bruijne 2012; Gaia Collaboration et al. 2016, 2018, 2021) and optical and infrared (IR) photometry from wide-field surveys, including the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), the United Kingdom Infrared Telescope Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007), the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010), Pan-STARRS1 (Kaiser et al. 2002, 2010), and the Visible and Infrared Survey Telescope for Astronomy (VISTA) Hemisphere Survey (VHS; McMahon et al. 2013). In previous studies, we have used those data to select candidate members of Ophiuchus and Upper Sco, many of which were then observed with spectroscopy (Esplin et al. 2018; Luhman et al. 2018; Esplin & Luhman 2020; Luhman & Esplin 2020). Meanwhile, we have identified candidates toward the Lupus clouds using data from the Gaia’s second data release (Luhman 2020) and have performed similar analysis for all populations in Sco-Cen with the early installment of the third data release of Gaia (EDR3; Luhman 2021a). Other recent studies also have searched for members of Sco-Cen using deep optical and IR imaging (Lodieu et al. 2018, 2021) and Gaia data (Cook et al. 2017; Goldman et al. 2018; Manara et al. 2018; Röser et al. 2018; Cánovas et al. 2019; Damiani et al. 2019; Galli et al. 2020; Teixeira et al. 2020; Grasser et al. 2021; Kerr et al. 2021). In this work, we present spectroscopy of a few hundred candidate members of Sco-Cen from our previous surveys with the goal of improving the completeness of the spectroscopic samples in those regions.

2. Spectroscopy of Candidates

2.1. Selection of Candidates

We have pursued spectroscopic of candidate members of Sco-Cen to measure their spectral types and assess their youth. We selected the candidates from our surveys of Sco-Cen (e.g., Esplin & Luhman 2020; Luhman & Esplin 2020; Luhman 2020, 2021a), giving the highest priority to candidates located within the Ophiuchus field from Esplin et al. (2018), the triangular field from Luhman & Esplin (2020) that encompasses the central concentration of stars in Upper Sco, and the fields toward Lupus clouds 1–4 from Luhman (2020). We focused on candidates that lack spectroscopic data, but we included stars that have previous classifications (primarily in Lupus) because they were sufficiently bright for poor observing conditions.
2.2. Observations

We have obtained 293 spectra for 284 candidates in Sco-Cen. Nine objects were observed with both optical and IR spectrographs. The observations were performed with the 4 m Blanco telescope at the Cerro Tololo Inter-American Observatory (CTIO), the NASA Infrared Telescope Facility (IRTF), and the Gemini North telescope. The instrument configurations are summarized in Table 1. The COSMOS observations with the 0/9 and 1/2 slits were performed on 2021 June 19–21 and 24/26, respectively. We have made use of archival data for one additional object that was observed through program 085.C-0887(A) (M. Fang) with the Infrared Spectrometer and Array Camera (Moorwood et al. 1998) at the Unit Telescope 4 of the Very Large Telescope at the European Southern Observatory. The configuration of that instrument produced a spectrum covering the $H$ and $K$ bands with a resolution of ~1000. The 285 spectroscopic targets are listed in Table 2, which includes the instruments and dates for their observations.

We reduced the IRTF/Spex data with the Spextool package (Cushing et al. 2004), which included correction of telluric absorption (Vacca et al. 2003). The CTIO/ARCiris spectra were reduced with a modified version of Spextool. The spectra from the remaining instruments were reduced using routines within IRAF. Examples of the reduced optical and IR spectra are presented in Figures 1 and 2, respectively. The reduced spectra are available in electronic files associated with those figures. Due to a malfunction, the telescope was not well-focused during the COSMOS observations on June 19–21. As a result, the slit loss varied with wavelength, and hence the slopes of those spectra are not reliable.

2.3. Spectral Classifications

We have analyzed the spectra with the same methods used in our previous surveys in Sco-Cen and other star-forming regions (e.g., Esplin et al. 2018; Luhman et al. 2018). In summary, we examined diagnostics of youth in the form of Li absorption at 6707 Å and gravity-sensitive features like the Na doublet near 8190 Å and the near-IR H$_2$O absorption bands. The use of Li and Na for constraining ages is illustrated in Figure 3, where we plot the equivalent widths of those lines versus spectral type for the targets with optical spectra. We have included the upper envelopes for Li data in IC 2602 (30 Myr) and the Pleiades (125 Myr) from Neuhäuser et al. (1997), and Na data for a sample of standard field dwarfs from our previous surveys and Filippazzo et al. (2016). All of the Li detections are stronger than the upper envelope for IC 2602, and thus are taken as evidence of youth. Meanwhile, all of the stars with Na measurements but no useful constraints on Li have sufficiently weak Na relative to the field dwarfs to indicate that they are probably young. We have measured spectral types through comparison to standard spectra for field dwarfs (Kirkpatrick et al. 1991, 1997; Henry et al. 1994; Cushing et al. 2005; Rayner et al. 2009) and members of star-forming regions (Luhman et al. 1997; Luhman & Rieke 1999; Luhman et al. 2017). We present our measurements of spectral types, equivalent widths of Li and Na, and assessments of youth in Table 2. The latter are based on our spectra as well as age

### Table 1

| Telescope/Instrument | Disperser/Slit | Wavelengths/Resolution | Targets |
|----------------------|---------------|------------------------|---------|
| CTIO 4 m/COSMOS      | red VPH/0/9 slt | 0.55–0.95 μm/3 Å       | 19      |
| CTIO 4 m/COSMOS      | red VPH/1/2 slt | 0.55–0.95 μm/4 Å       | 36      |
| CTIO 4 m/ARCiris     | 110.51 mm$^{-1}$ + prism/1/2 slt | 0.8–2.47 μm/R = 3500 | 8       |
| Gemini North/GNIRS   | 37.11 mm$^{-1}$/1' slt | 0.9–2.5 μm/R = 600 | 14      |
| IRTF/Spex            | prism/0/8 slt | 0.8–2.5 μm/R = 150     | 216     |

**Note.**

a The Gemini Near-Infrared Spectrograph (GNIRS) and SpeX are described by Elias et al. (2006) and Rayner et al. (2003), respectively. The Cerro Tololo Ohio State Multi-Object Spectrograph (COSMOS) is based on an instrument described by Martini et al. (2011).

### Table 2

| Column Label | Description |
|--------------|-------------|
| Gaia         | Gaia EDR3 source name |
| UGCS         | UKIDSS Galactic Clusters Survey source name |
| 2MASS        | 2MASS Point Source Catalog source name |
| Name         | Other source name |
| RAdeg        | Right ascension (ICRS)$^a$ |
| DEdeg        | decl. (ICRS)$^a$ |
| Ref-Pos      | Reference for R.A. and decl.$^a$ |
| SpType       | Spectral type from this work$^b$ |
| EWLi         | Flag for EWLi |
| EWLion       | Equivalent width of Li$^c$ |
| EWNa         | Equivalent width of Na$^c$ |
| Instrument   | Instrument used for spectral classification |
| Date         | Date of spectroscopy |
| Young        | Is the candidate young based on spectroscopy or other diagnostics? |
| Kin          | Kinematic population$^d$ |
| Pos          | Position in Sco-Cen$^d$ |

**Notes.** The table is available in its entirety in machine-readable form.

$^a$ Sources of the right ascension and declination are Gaia EDR3 (Epoch 2016.0), DR10 of the UKIDSS Galactic Clusters Survey, and the 2MASS Point Source Catalog.

$^b$ Uncertainties are 0.25 and 0.50 subclass for optical and IR spectral types, respectively, unless indicated otherwise.

$^c$ Typical uncertainties are 0.05 and 0.3 Å for Li and Na, respectively.

$^d$ Parallax and proper motion offset from Gaia EDR3 are consistent with membership in these Sco-Cen populations based on the criteria in Luhman (2021a): u = Upper Sco; o = Ophiuchus; l = Lupus; v = V1062 Sco; c = UCL/LCC; n = none of these populations.

$^e$ Celestial coordinates within these regions: o = the Ophiuchus field from Esplin et al. (2018); u = the triangular field in Upper Sco from Luhman & Esplin (2020), excluding Ophiuchus; l = the fields encompassing Lupus clouds 1–4 from Luhman (2020). (This table is available in its entirety in machine-readable form.)
constraints available from previous work. Most of the objects (269/285) have evidence of youth.

Table 2 contains a flag that indicates the populations in Sco-Cen with which the kinematic data from Gaia EDR3 are consistent based on the analysis in Luhman (2021a) and a flag that indicates whether each object is within the fields in Ophiuchus, Upper Sco, and Lupus, mentioned in Section 2.1. The kinematic flag is absent for objects that lack parallax measurements with errors of <1 mas from Gaia EDR3. Eight of the spectroscopic targets are flagged as nonmembers for Sco-Cen based on data from Gaia EDR3.

2.4. Classifications of Spectra from Previous Studies

In addition to the spectra collected in this work, we have classified IR spectra from previous studies for several candidates for substellar members of Ophiuchus and Upper Sco. They consist of three sources toward Ophiuchus that were classified as young by Allers & Liu (2020) and that we have not classified previously: the two candidate members of Upper Sco that were observed spectroscopically by Lodieu et al. (2021), and three highly reddened objects toward Ophiuchus that have been described as protostellar brown dwarfs by Whelan et al. (2018) and Riaz & Bally (2021) and that exhibit absorption features in spectra from those studies.

We have classified the spectra from Allers & Liu (2020) and Lodieu et al. (2021) through comparison to the young standard spectra from Luhman et al. (2017). The resulting spectral types are similar to those from Allers & Liu (2020) and are earlier than those from Lodieu et al. (2021). In Figure 4, we present the spectrum of one of the two objects from Lodieu et al. (2021), UGCS J161110.14−214516.8, and we include comparisons to standard spectra for M9, L0, and L2. The M9 and L0 spectra have been reddened to match the slope of UGCS J161110.14−214516.8 while no reddening is needed for the L2 spectrum. The three standards in Figure 4 provide similar fits, which illustrates the degeneracy between spectral type and reddening for young L dwarfs (Luhman et al. 2017). Lodieu et al. (2021) classified UGCS J161110.14−214516.8 as L6, but the standards later than L2 from Luhman et al. (2017) are too red to match its slope.
The spectra of ISO Oph 70, 200, and 203 from Whelan et al. (2018) and Riaz & Bally (2021) contain absorption features that can be used to constrain the spectral types of the stars, which was not attempted in those studies. Among the detected absorption lines, the most useful ones for spectral classification are produced by Ca, Mg, and CO in the K band. In Figure 5, we show the spectra for a wavelength range encompassing those features. To facilitate comparison to standard spectra, the spectra have been divided by low-order fits to the continua. The sources exhibit large IR excesses (Bontemps et al. 2001; Dunham et al. 2008), so the observed K-band spectra may include continuous emission from circumstellar dust, which would dilute the absorption lines from the stellar photospheres. The lines in Figure 5 span a small enough range of wavelengths that they should be subjected to the same degree of continuum veiling, in which case the relative line strengths will be independent of veiling. We have estimated spectral types from those relative strengths through comparison to spectra of young stars that have optical spectral types (e.g., Covey et al. 2010; Allers & Liu 2013). For all three objects, we find that the lines are best fit by spectral types of early M. To illustrate these fits, we have included in Figure 5 comparisons to a spectrum of the young star TWA 25 (M0.75; Zuckerman & Song 2004; Luhman et al. 2017) after the application of continuum veiling, which is quantified as $r_K = I_{2.2}$(IR excess)/$I_{2.2}$(star). In addition, we show comparisons to the young brown dwarf TWA 26 (M8.5, Gizis 2002; Luhman et al. 2017), which differs significantly from the Ophiuchus sources in terms of the relative strengths of Ca and CO. The Ophiuchus objects are likely to be younger than the association containing TWA 25 and TWA 26 (~10 Myr; Webb et al. 1999; Mamajek 2005), in which case they would have lower surface gravities. However,
late-M objects with lower gravities would produce worse fits since they would have even stronger CO bands. In our low-resolution IR spectrum of ISO Oph 200, the CO bands are in emission rather than absorption, indicating the presence of strongly variable emission in that feature from circumstellar material. Indeed, in the spectrum of that object in Figure 5, the first bandhead of absorption at 2.29 μm appears to contain weak emission within it. Accounting for such line veiling of CO could improve the match to a late-M type, but the relative strengths of Ca and the other features at <2.29 μm would remain discrepant.

The spectral types of early M that we derive for ISO Oph 70, 200, and 203 should correspond to masses in the vicinity of 0.6 M_☉ based on the temperatures predicted for ages of ≤10 Myr by theoretical evolutionary models (Baraffe et al. 1998, 2015). Young brown dwarfs are expected to have spectral types of ≥M6.5, which are inconsistent with the spectra of those sources. The substellar masses previously reported for ISO Oph 70, 200, and 203 have been derived from estimates of their bolometric luminosities using predicted relations between luminosity and mass for protostars (Riaz & Bally 2021). However, the luminosities of protostars can be underestimated if they are detected primarily in scattered light at the near-IR wavelengths where photospheric fluxes are measured. In addition, the predicted relations between luminosity and mass for protostars are uncertain (Dunham et al. 2014).

The spectral types that we have measured in this section are included in Table 3, where we compile spectral types from this work and previous studies for all objects toward Upper Sco and Upper Sco that have spectral classifications and evidence of youth.

3. Status of Spectroscopic Samples in Sco-Cen

3.1. Compilations of Spectroscopically Classified Stars

Recent studies have presented compilations of candidate members of Ophiuchus, Upper Sco, and Lupus that have been observed spectroscopically and that exhibit evidence of youth (Esplin & Luhman 2020; Luhman & Esplin 2020). In addition, Luhman (2021a) has performed a census of all of the Sco-Cen populations using Gaia EDR3 and has compiled the spectral types that are available (including those from this work) for the resulting candidates. In Tables 3 and 4, we present our latest compilations of candidate members of Ophiuchus/Upper Sco and Lupus, respectively, that have spectral classifications and that satisfy the following additional criteria. We have only considered Ophiuchus and Upper Sco candidates that are within the boundary of Upper Sco from de Zeeuw et al. (1999; l = 343°–360°, b = 10°–30°) and Lupus candidates that are within the fields toward clouds 1–4 from Luhman (2020). The Ophiuchus/Upper Sco and Lupus catalogs contain objects that have spectroscopy and that (1) lack Gaia EDR3 astrometry and have evidence of youth or (2) have Gaia EDR3 parallaxes and proper motions that satisfy the criteria for membership in Ophiuchus/Upper Sco or Lupus (Luhman 2021a) and that have evidence of youth or lack constraints on youth. One consequence of these criteria is that they exclude young stars projected against Ophiuchus, Upper Sco, and Lupus that have astrometry indicative of other populations in Sco-Cen. For close pairs that are resolved by Gaia but were likely unresolved during the spectroscopy, we have listed only the components that are brighter in the G band from Gaia. The catalog of Sco-Cen candidates in Luhman (2021a) includes the fainter components of such pairs if they satisfy the kinematic criteria for membership. The contents of Tables 3 and 4 consist of source names from Gaia EDR3, UKIDSS (for Ophiuchus Upper Sco), 2MASS, and various other catalogs, equatorial coordinates, available spectral types, our adopted classifications, and a flag indicating the populations with which the kinematic data from Gaia EDR3 are consistent. In Table 3, we also include a flag indicating whether each object is located in the Ophiuchus field from Esplin et al. (2018) or the triangular Upper Sco field from Luhman & Esplin (2020). The catalogs for Ophiuchus, Upper Sco, and Lupus contain 419, 1723, and 132 sources, respectively; 61, 237, and 20 of which are later than M6.

![Figure 5](image-url)
Table 3  
Candidate Members of Ophiuchus and Upper Sco with Spectral Classifications at $l = 343\degree-360\degree$ and $b = 10\degree-30\degree$.

| Column Label | Description |
|--------------|-------------|
| Gaia         | Gaia EDR3 source name |
| UGCS         | UKIDSS Galactic Clusters Survey source name |
| 2MASS        | 2MASS Point Source Catalog source name |
| Name         | Other source name |
| RAdeg        | Right ascension (ICRS) |
| Decl         | decl. (ICRS) |
| Ref Pos      | Reference for R.A. and decl.² |
| SpType       | Spectral type |
| r,SpType     | Spectral type reference³ |
| Adopt        | Adopted spectral type |
| Kin          | Kinematic population⁴ |
| Pos          | Position in Sco-Cen⁵ |

Notes. The table is available in its entirety in machine-readable form.

² Sources of the R.A. and decl. are Gaia EDR3 (Epoch 2016.0), DR6 of VISTA VHS, DR10 of the UKIDSS Galactic Clusters Survey, the 2MASS Point Source Catalog, and high-resolution imaging (Ireland et al. 2011; Kraus et al. 2014; Lachapelle et al. 2015; Bryan et al. 2016).
³ (1) Houk & Smith-Moore (1988); (2) Cannon & Pickering (1993); (3) Luhman et al. (2018); (4) Dawson et al. (2014); (5) Esplin et al. (2018); (6) Luhman & Esplin (2020); (7) Rizzuto et al. (2015); (8) Preibisch et al. (1998); (9) Lodieu et al. (2008); (10) Bonnefoy et al. (2014); (11) this work; (12) Lodieu et al. (2006); (13) Kunkel (1999); (14) Hiltner et al. (1969); (15) Pecaut & Mamajek (2016); (16) Peña Ramirez et al. (2016); (17) Houk (1982); (18) Corbally (1984); (19) Aller et al. (2013); (20) Martin et al. (2004); (21) Martin et al. (2010); (22) Slenich et al. (2008); (23) Chinchilla et al. (2020); (24) Preibisch et al. (2002); (25) Mora et al. (2001); (26) Vieira et al. (2003); (27) Reid et al. (2008); (28) Ardila et al. (2000); (29) Walter et al. (1994); (30) Kirkpatrick et al. (2010); (31) Allers & Liu (2013); (32) Faherty et al. (2016); (33) Torres et al. (2006); (34) Gizis et al. (2002); (35) Herczeg & Hillenbrand (2014); (36) Slenich et al. (2006); (37) Riaz et al. (2006); (38) Best et al. (2017); (39) Lodieu et al. (2018); (40) Kraus et al. (2014); (41) Cody et al. (2017); (42) Lafrenière et al. (2011); (43) Lachapelle et al. (2015); (44) David et al. (2019); (45) Ansdell et al. (2016); (46) Prato et al. (2002); (47) Preibisch et al. (2001); (48) Cruz et al. (2003); (49) Béjar et al. (2008); (50) Herczeg et al. (2009); (51) Lodieu et al. (2021); (52) measured in this work with the most recently published spectrum; (53) Kraus & Hillenbrand (2007); (54) Lodieu et al. (2011); (55) Müller et al. (2011); (56) Kraus & Hillenbrand (2009); (57) Pecaut et al. (2012); (58) Biller et al. (2011); (59) Lafrenière et al. (2008); (60) Luhman et al. (2017); (61) Mann et al. (2016); (62) David et al. (2016b); (63) Stauffer et al. (2017); (64) Stauffer et al. (2018); (65) Cohen & Kihl (1979); (66) Prato et al. (2003); (67) Eisner et al. (2005); (68) Murphy (1969); (69) Martín et al. (1998); (70) Lafrenière et al. (1997); (71) Prato (2007); (72) McClure et al. (2010); (73) Lodieu et al. (2015); (74) David et al. (2016a); (75) Carpenter et al. (2006); (76) Luhman (2005); (77) Martín (1998); (78) Esplin & Luhman (2020); (79) Allers & Liu (2020); (80) Cieza et al. (2010); (81) Bowler et al. (2011); (82) Bowler et al. (2014); (83) Romero et al. (2012); (84) Allen et al. (2007); (85) Merin et al. (2010); (86) Erickson et al. (2011); (87) Wilking et al. (2005); (88) Brandner & Zinnecker (1997); (89) Maheswar et al. (2003); (90) Alves de Oliveira et al. (2012); (91) Greene & Meyer (1995); (92) Luhman & Rieke (1999); (93) Bouvier & Appenzeller (1992); (94) Alves de Oliveira et al. (2010); (95) Struve & Rudjakpobing (1949); (96) Muzi’ic et al. (2012); (97) Wilking et al. (1999); (98) Natta et al. (2002); (99) Manara et al. (2015); (100) Testi et al. (2002); (101) Comerón et al. (2010); (102) Cushing et al. (2000); (103) Bowler et al. (2017); (104) Luhman et al. (1997); (105) Geers et al. (2011); (106) Gatti et al. (2006); (107) Geers et al. (2007); (108) Paterne et al. (1993); (109) Vrba et al. (1993); (110) Rydgren (1980).

³ Parallax and proper motion offset from Gaia EDR3 are consistent with membership in these Sco-Cen populations based on the criteria in Luhman (2021a): $u = \text{Upper Sco}; o = \text{Ophiuchus}; l = \text{Lupus}; v = \text{V1062 Sco}; \zeta = \text{UCL-LCC}.$

⁴ Celestial coordinates within these regions: $o = \text{the Ophiuchus field from Esplin et al. (2018)}; u = \text{the triangular field in Upper Sco from Luhman & Esplin (2020)}$, excluding Ophiuchus.

This table is available in its entirety in machine-readable form.

3.2. Completeness of Spectroscopic Samples

We wish to characterize the completeness of the spectroscopic samples in the Ophiuchus field from Esplin et al. (2018), the triangular field in Upper Sco from Luhman & Esplin (2020), and the fields toward Lupus clouds 1–4 from Luhman (2020). To do that, we employ color–magnitude diagrams (CMDs) constructed from $H$ and $K_S$ because they provide the best sensitivity to members of these regions given the typical colors of young stars and the depths of the available imaging surveys. We use photometry from 2MASS, UKIDSS, and VHS for Ophiuchus and Upper Sco and photometry from 2MASS for Lupus. We present diagrams of $K_S$ versus $H - K_S$ for the fields in Ophiuchus, Upper Sco, and Lupus in Figures 6, 7, and 8, respectively. For the Ophiuchus and Upper Sco CMDs, we have marked the completeness limit estimated for the UKIDSS data by Luhman & Esplin (2020). For the Lupus CMD, we show the completeness limit for 2MASS from Skrutskie et al. (2006). The CMDs contain the sources with spectral classifications from Tables 3 and 4 that are located within the fields in question, which are plotted with blue and red points for spectral types of $\leq$M6 and $>$M6, respectively. We also have included all other sources in the fields with the exception of those that (1) have data indicating that they are not young, (2) have kinematics from Gaia EDR3 that are inconsistent with membership (Luhman 2021a), (3) are resolved as galaxies in available imaging, (4) are rejected by CMDs from the imaging surveys mentioned in Section 1 (Luhman et al. 2018; Esplin & Luhman 2020; Luhman & Esplin 2020), or (5) appear below the dashed line in the CMDs in Figures 6–8, which was selected by Luhman et al. (2018) to follow the lower envelope of the sequence of known members of Upper Sco and Ophiuchus.

In the CMD for Ophiuchus, the number of sources that lack spectra is fairly small relative to the spectroscopic sample for a wide range of magnitudes and reddenings. The CMD indicates
that the spectroscopic sample has a high level of completeness for an extinction-corrected magnitude of $K < 15.5$ for $A_K < 0.8$. There are 44 objects that lack spectra at $H - K_s < 2$ and $K_s < 15$, 18 of which have Gaia data that support membership, making them strong candidates. All of those Gaia candidates have $H - K_s < 1.3$ and $K_s \lesssim 12$. Many of the redder objects without spectral classifications are also probable members based on IR excesses and other signatures of youth (e.g., outflows). The CMD for Upper Sco is high at $K_s \lesssim 15.5$. Between $K_s = 15.5$ and the magnitude at which the UKIDSS completeness limit intersects with the Upper Sco sequence ($K \sim 16.5$), the numbers of objects with spectra and without spectra are roughly similar. Finally, the Lupus CMD suggests that the spectroscopic sample is complete down $K_s \sim 13$ for low extinctions ($A_K < 0.2$). For the range of extinctions exhibited by most members ($A_K < 0.5$), the sample should be mostly complete for an extinction-corrected magnitude of $K_s \sim 13$.

Assuming the median distances of the populations and the $K$-band bolometric correction for young late-type objects (Filippazzo et al. 2015), the completeness limits of $K_s = 15.5, 15.5$, and 13 for Ophiuchus, Upper Sco, and Lupus from the preceding analysis correspond to masses of $\sim 0.008$, 0.014, and 0.035 $M_\odot$ for ages of 3, 10, and 5 Myr, respectively (Chabrier et al. 2000; Baraffe et al. 2015).

3.3. Prospects for Future Spectroscopy in Sco-Cen

The completeness of the spectroscopic samples in Ophiuchus and the center of Upper Sco can be improved by obtaining spectra of the remaining candidates at $K_s < 15$ discussed in the previous section. The completeness limits of those samples and the sample in Lupus can be extended to fainter magnitudes through deeper optical and IR imaging and spectroscopy of the resulting candidates. Outside of the fields in Ophiuchus, Upper Sco, and Lupus in which we have examined completeness, several thousand candidate members of Sco-Cen have been identified using data from Gaia EDR3 (Luhman 2021a), most of which lack spectral classifications. The most appealing
subsets for spectroscopy include the hundreds of candidates that have IR excesses from disks (Luhman 2021b), particularly in the oldest populations of V1062 Sco and UCL/LCC, and the hundreds of candidates with colors indicative of brown dwarfs ($\gtrsim$M6.5).

4. Conclusions

We have presented optical and IR spectroscopy of 285 candidate members of the Sco-Cen complex that have been identified in our previous studies. The results are summarized as follows:

1. We have measured spectral types for the Sco-Cen candidates and have assessed their youth using spectral diagnostics and other available data. Evidence of youth is found for 269 of the 285 candidates. In addition, we have compiled all objects with spectral classifications and evidence of youth in Ophiuchus, Upper Sco, and the fields toward Lupus clouds 1–4 from Luhman (2020). The resulting catalogs contain 419, 1723, and 132 sources for the three regions, respectively; 61, 237, and 20 of which are later than M6.

2. We have classified IR spectra from previous studies for several candidates for substellar members of Ophiuchus and Upper Sco. In the most notable result, we find that three sources in Ophiuchus that have been proposed to be protostellar brown dwarfs (ISO Oph 70, 200, 203) have spectral types of early M, which are earlier than expected for young brown dwarfs based on evolutionary models ($\gtrsim$M6.5) and instead are indicative of stellar masses ($\sim$0.6 M$_\odot$).

3. We have used near-IR CMDs to characterize the completeness of the spectroscopic samples in the Ophiuchus field from Esplin et al. (2018), the triangular field in Upper Sco from Luhman & Esplin (2020), and the fields toward Lupus clouds 1–4 from Luhman (2020). Those samples have high levels of completeness at $K_s < 15.5$, 15.5 and 13 for Ophiuchus, Upper Sco, and Lupus, respectively, for the ranges of extinctions encompassing most members. Those magnitudes correspond to masses of $\sim$0.008, 0.014, and 0.035 M$_\odot$ for ages of 3, 10, and 5 Myr, respectively, based on evolutionary models (Chabrier et al. 2000; Baraffe et al. 2015).

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