IN-SYNC IV. THE YOUNG STELLAR POPULATION IN THE ORION A MOLECULAR CLOUD

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Received 2015 September 11; accepted 2015 December 10; published 2016 February 8

ABSTRACT

We present the results of the Sloan Digital Sky Survey APOGEE INfrared Spectroscopy of Young Nebulous Clusters program (IN-SYNC) survey of the Orion A molecular cloud. This survey obtained high-resolution near-infrared spectroscopy of about 2700 young pre-main-sequence stars on a ~6° field of view. We have measured accurate stellar parameters (Teff, log g, v sin i) and extinctions and placed the sources in the Hertzsprung–Russel diagram (HRD). We have also extracted radial velocities for the kinematic characterization of the population. We compare our measurements with literature results to assess the performance and accuracy of the survey. Source extinction shows evidence for dust grains that are larger than those in the diffuse interstellar medium: we estimate an average Rv = 5.5 in the region. Importantly, we find a clear correlation between HRD inferred ages and spectroscopic surface-gravity-inferred ages and between extinction and disk presence; this strongly suggests a real spread of ages larger than a few Myr. Focusing on the young population around NGC 1980/i. Ori, which has previously been suggested to be a separate, foreground, older cluster, we confirm its older (~5 Myr) age and low Av, but considering that its radial velocity distribution is indistinguishable from Orion A’s population, we suggest that NGC 1980 is part of Orion A’s star formation activity. Based on their stellar parameters and kinematic properties, we identify 383 new candidate members of Orion A, most of which are diskless sources in areas of the region poorly studied by previous works.

Key words: open clusters and associations: individual (Orion Nebula Cluster, L1641) – stars: formation – stars: kinematics and dynamics – stars: pre-main sequence

Supporting material: machine-readable tables

1. INTRODUCTION

Young stellar populations are the immediate product of converting gas in molecular clouds into stars and therefore provide critical information on how star formation progresses over time and space. Despite recent advances that have been made in this field, including observational and theoretical work focusing on the different stages of star formation, a number of mechanisms remain unclear. It is still debated whether star formation is a fast, dynamic process (Elmegreen 2000, 2007; Hartmann & Burkert 2007) or slow (Tan et al. 2006; Da Rio et al. 2014a), proceeding for at least several dynamical timescales. In this context, the systematic, unbiased assessment of stellar ages and age spreads in young pre-main-sequence (PMS) populations is fundamental (Da Rio et al. 2010a, 2014a), though not easy given our poor understanding of PMS evolution and its dependence on the earlier protostellar properties and accretion histories (Baraffe et al. 2009, 2012). The star formation efficiency, both per free-fall time tff (Tan et al. 2006; Da Rio et al. 2014b) and on an absolute scale, as the fraction of parental gas converted into stars, and especially their environmental dependence are not fully understood. These fundamental properties are also important factors in the survivability of a young population as a bound cluster (Lada & Lada 2003; Baumgardt & Kroupa 2007; Kroupa 2012). This is further complicated considering that observational evidence has shown that star formation typically occurs in filamentary structures that can show significant substructure at early phases (e.g., André 2015; Hacar et al. 2013; Henshaw et al. 2014). Such structures may then also merge in relatively short timescales, erasing the information on their initial morphology (Parker & Meyer 2012; Da Rio et al. 2014b; Parker 2014; Jaehnig et al. 2015).

The upcoming Gaia mission will help constrain the kinematic properties of nearby young populations through accurate proper motions and parallactic distances; however, it will not perform well for young clusters still embedded in their parental material. Similarly, most ground-based radial velocity surveys have adopted optical spectroscopy (Tobin et al. 2009; Gilmore...
et al. 2012; Jeffries et al. 2014). Recently, the IN-SYNC survey used the capabilities of the SDSS-III Apache Point Observatory Galactic Evolution Experiment (APOGEE) to obtain multi-object near-infrared (NIR) high-resolution spectra to obtain stellar parameters and radial velocities in young clusters. The first part of this survey covered the Perseus cloud, through their young clusters IC 348 (Cottaar et al. 2014, 2015, hereafter Paper I and Paper II) and NGC 1333 (Foster et al. 2015, hereafter Paper III). In these studies we have demonstrated the abilities of APOGEE to study the stellar properties in young clusters, assess their age spread, and compare the kinematic properties of young stars with those of the remaining gaseous material. We have found evidence for a supervirial stellar population in IC 348, whereas in NGC 1333 the stars are in agreement with virial velocities, but the diffuse gas and dense gas have significantly different velocity dispersion. As for the comparison between stellar and gas kinematics, Paper II found that stars in NGC 1333 show a similar velocity dispersion to the diffuse gas, whereas the young dense cores in the region have much slower, subvirial motions. In a second phase of the IN-SYNC collaboration we have extended our survey to the Orion A molecular cloud.

The Orion molecular complex is a large structure, at a distance of ∼400 pc (Menten et al. 2007; Schlafly et al. 2014), which has sustained star formation in different locations for over 15 Myr (Blaauw 1964, 1991; Muench et al. 2008, p. 483). The oldest young populations, such as λ Ori, σ Ori, and 25 Ori, are mostly disassociated from the molecular material. Two main regions of dense molecular gas, referred to as Orion A and Orion B, host young (few Myr) stellar populations with ongoing star formation (Lombardi et al. 2011, 2014; Megeath et al. 2012; Stutz et al. 2013; Stutz & Kainulainen 2015). Of these two, the 40 pc long Orion A filament has the highest star formation rate. The densest region in Orion A, the Orion Nebula Cluster (ONC), is the closest site of active massive star formation, where young stars span the mass spectrum up to ~40 M⊙ (Grellmann et al. 2013). Sparser populations are present to the north, in the upper sword and NGC 1977, and to the south, with NGC 1980 and L1641. All these populations have been long studied through photometric and spectroscopic studies (Hillenbrand 1997; Hillenbrand & Hartmann 1998; Fang et al. 2009, 2013; Da Rio et al. 2010a, 2012; Robberto et al. 2010, 2013; Hsu et al. 2012, 2013), at longer wavelengths (Megeath et al. 2012; Lombardi et al. 2014), and in the X-rays (Getman et al. 2005; Pillitteri et al. 2013). The PMS population throughout the region spans approximately the same age of a few Myr (Da Rio et al. 2010a; Fang et al. 2013), with the exception of the region around λ Ori, to the immediate south of the ONC, where Alves & Bouy (2012) and Bouy et al. (2014) claim that the population is slightly older and possibly in foreground, owing to the low average A_V of the members. The initial mass function (IMF) is found to be compatible with the Kroupa (2001) IMF in the ONC, although is found to be deficient in the substellar regime (Da Rio et al. 2012). In L1641, however, Hsu et al. (2013) note that despite the large number of PMS members in this region (exceeding 10^3 stars), no massive stars are present. This would suggest an upper truncation of the IMF, possibly due to lower-density conditions.

Kinematic studies based on radial velocities have been so far limited to the north part of the cloud, with a field of view (FOV) of 2° in declination. Fűrész et al. (2008) and Tobin et al. (2009) collected velocities through optical high-resolution spectroscopy for over 1600 sources. They measured an average velocity dispersion σ_v ~ 2.3 km s^{-1}, consistent with proper-motion measurements in the ONC (Jones & Walker 1988). They also noted that stars in this region are systematically blueshifted by ~1 km s^{-1} relative to the local gas.

In this work we extend over previous studies and present the results from the IN-SYNC Orion survey, including the study of the stellar population, extinction law, ages and age spreads, and new memberships from a combination of indicators. In a subsequent paper we will focus on the APOGEE radial velocities to characterize the kinematic status of the entire region, in comparison with the molecular gas.

In Section 2 we present the data and extraction of stellar parameters. In Section 3 we compare the stellar parameters we derived with literature results for a subset of targets, in order to assess the accuracy of our measurements, and estimate the incidence of contaminants. In Section 4 we explore the age and age spread properties of the entire population. Finally, in Section 5 we utilize our measurements to recover new candidate members from sources previously unclassified.

2. THE DATA

Observations were carried out in 2013 December and 2014 January, with the APOGEE spectrograph (Wilson et al. 2010, 2012) on the Sloan 2.5 m telescope (Gunn et al. 2006). APOGEE is a fiber-fed multiobject infrared spectrograph, operating in H band in the range 1.5 μm ≤ λ ≤ 1.6 μm, capable of obtaining spectra of up to 320 sources simultaneously on a corrected FOV of ~7 square degrees, and with a resolution λ/Δλ ≈ 22,500. More information on this instrument, the standard observing procedures, the data reduction pipeline, and the resulting spectra and catalogs can be found on the SDSS-III Web site (http://www.sdss3.org) and in the APOGEE technical papers (Zasowski et al. 2013; Holtzman et al. 2015; Nidever et al. 2015).

Fifteen APOGEE plates, on five positions in the sky (see Table 1), have been designed to cover the Orion A region as shown in Figure 1. The area covered has been isolated to match the Two Micron All Sky Survey (2MASS) sources with H < 12.5, using an automatic procedure. This aimed at maximizing the number of allocated fibers per plate while also accounting for priority rankings among the individual sources. To this end, we developed an automatic stochastic fiber allocation method. For each plate, a random observable source

| Center | α (J2000) | δ (J2000) | Number of Plates |
|--------|-----------|-----------|------------------|
| A      | 05°36'24" | -05°06'00" | 5                |
| B      | 05°34'12" | -05°18'00" | 5                |
| C      | 05°37'00" | -06°54'00" | 2                |
| D      | 05°38'00" | -07°12'00" | 1                |
| E      | 05°40'48" | -08°42'00" | 2                |
is considered. Then, based on targeting probability defined for that star, it is randomly kept, allocating a fiber to it, or rejected. If rejected, the star will still be available for subsequent iteration of the method, which continues until all available fibers have been allocated. The targeting probabilities have been tuned after several attempts to achieve a sensible overall targeting. Known members from optical studies, in the ONC (Da Rio et al. 2010b, 2012) or in L1641 (Fang et al. 2009, 2013; Hsu et al. 2012, 2013), with available stellar parameters were given the highest priority. Additional sources with IR-excess (Megeath et al. 2012) or X-ray emission (Getman et al. 2005; Pillitteri et al. 2013) were a lower probability. Stars in the crowded core of the ONC were also ranked higher, to compensate for the intrinsic difficulty in targeting them owing to the large exclusion radius (~1.2) from fiber collision on the APOGEE plates. This involved multiplying the targeting population probabilities by a factor that continuously depends on the number of neighbors in the vicinity of each source. Unlike the IN-SYNC Perseus survey, in Orion we prioritized the number of individual sources observed over the repetition of the same sources at different epochs. Thus, targeting probability of each star is reduced 50 times if the star was already targeted by a different plate, or only 10 times for sources at the faint end of the APOGEE luminosity range (11.5 < H < 12.5) to improve their signal-to-noise ratio (S/N). All the plates were filled with 320 targets, plus additional sky and telluric fibers. Figure 1 shows the spatial distribution of the targeted sources, superimposed on a 13CO map from Nishimura et al. (2015), highlighting the previously known members, as well as the number of epochs observed for the same star. Hereafter we will refer to sources as “known members” if they satisfy any of the following criteria.

1. IR excess, from the 2MASS and Spitzer survey of Megeath et al. (2012).
2. X-ray sources matching optical or IR photometry, in the ONC from the COUP survey (Getman et al. 2005), Chandra observations in the ONC flanking fields (Ramírez et al. 2004), and XMM-Newton observations in L1641 (Pillitteri et al. 2013).
3. Sources in L1641 with spectroscopic evidence of youth, either lithium abundance or Hα excess (Fang et al. 2009, 2013), as well as additional candidate members from Hsu et al. (2012).
4. Additional ONC sources with Hertzsprung–Russell diagram (HRD) position consistent with the PMS sequence of the cluster (Da Rio et al. 2010b, 2012).

In Section 5 we will extend the sample of candidate members based on our data; however, in all material preceding Section 5 we will refer to these previously identified members as “known members.”

Figure 1. IN-SYNC Orion targets overplotted on the 13CO map from Nishimura et al. (2015). The left panel highlights the previously known young members from the literature (red circles) as opposed to targets of unknown memberships (blue). The right panel shows the targets color-coded according to the number of epochs in which each star has been observed. Circles indicate sources with H < 12.5 not targeted by our program. The green circles indicate the 2° FOVs, smaller than the full APOGEE FOV, to which we restricted our five pointing positions.
Figure 2 shows our targets in a 2MASS $JH$ color–magnitude diagram (CMD). Including telluric fibers in our FOV, we collected 4828 spectra of 2691 individual sources, 1704 of which were previously identified members from the literature. Thanks to our forced priority in targeting previously known members, we were able to cover most of them (80%–90%) within the entire region down to our selection limit $H < 12.5$, with the sole exception of the core of the ONC, where, as a result of crowding, the coverage drops to about half.

The raw data have been processed through the APOGEE pipeline described in Nidever et al. (2015), which corrects for instrumental effects and performs wavelength and flux calibration for each spectrum. Stellar parameters were then derived by us by comparison of our observations with BT-Settl synthetic spectra (Allard et al. 2011). We adopted a Markov Chain Monte Carlo (MCMC) algorithm to obtain the best fit, leaving $T_{\text{eff}}$ and $\log g$ free and constraining $[\text{M/H}] = 0$ as appropriate for the region (D’Orazi et al. 2009). Radial velocity $v_r$ and projected rotational velocity $v \sin i$ have also been left free; for the latter the models have been convolved with the rotational broadening profile from Gray (1992). Finally, a variable amount of flat flux excess has been added to the spectra and left as a free parameter, to emulate the amount of veiling—nonphotospheric flux excess originating from either circumstellar disk thermal emission or the accretion flow. Further details on the fitting procedure are presented in Paper I. As highlighted in that work, analyzing the parameters derived in all the IN-SYNC clusters compared to values reported in the literature for the same sources, we found systematic departures in our $v_r$ and $T_{\text{eff}}$ at the low end of the $T_{\text{eff}}$ scale and attributed them to inaccuracies of the BT-Settl synthetic models. As a matter of fact, these models have been shown to deviate from empirical data in the range $3000 \text{ K} \lesssim T_{\text{eff}} \lesssim 3500 \text{ K}$, both in the optical Da Rio et al. (2010b) and in the NIR, specifically in the $H$ band (Scandariato et al. 2012; Kopytova et al. 2013) where APOGEE operates.

Our MCMC algorithms naturally provides associated uncertainties for each fitted parameter. As described in Paper I, by studying the scatter in the best-fit parameters of the same star at different epochs, we found that this derived error represents an underestimate of the real error. A correction factor was applied to scale the MCMC error estimates to the empirical values empirically determined to depend on the $\chi^2$ value of each fit. Such a discrepancy, which we corrected for in our Orion data set as well, probably originates from the inability of the synthetic spectra to reproduce the real data.

3. STELLAR PARAMETERS

We have compared our derived stellar parameters with estimates from the literature, where available for a subsample of sources. In the ONC, stellar censuses have been collected from optical spectroscopy (Hillenbrand 1997; Da Rio et al. 2010b; Hillenbrand et al. 2013) and from narrowband photometry mapping temperature-sensitive TiO bands in the M-type range (Da Rio et al. 2010b, 2012); radial velocities have been collected by Sicilia-Aguilar et al. (2005), Führer et al. (2008), and Tobin et al. (2009). In L1641, optical spectroscopy was carried out by Fang et al. (2009, 2013) and Hsu et al. (2012, 2013), but no radial velocities have been collected for declinations $\delta < -6^\circ$.

3.1. Effective Temperature

Figure 3 shows the comparison of our derived effective temperatures ($T_{\text{eff}}$) and previous estimates. As discussed in Paper I for the Perseus survey, our APOGEE spectra are less accurate in deriving $T_{\text{eff}}$ for intermediate temperatures ($T_{\text{eff}} \gtrsim 4000 \text{ K}$), owing to the smaller number of features in the $H$-band spectra compared to colder sources; this is evident from Figure 3 as a large scatter in this $T_{\text{eff}}$ range. However, at increasing $T_{\text{eff}}$ the fraction of field contaminants increases (see below), such that most of the young Orion members are in the M-type range. Below 4000 K the agreement is much tighter, especially for ONC stars (Hillenbrand 1997; Da Rio et al. 2012; Hillenbrand et al. 2013), whereas the scatter increases for L1641 members. This indicates that the literature parameters in L1641 were less reliable than those for the ONC. The correlation is particularly tight when limiting to sources from Da Rio et al. (2012), with $T_{\text{eff}}$ derived from narrowband photometry, with an rms between new and old results of $\sim 100 \text{ K}$. The rms increases to $\sim 140 \text{ K}$ when comparing with optical spectroscopy from Hillenbrand (1997) and Hillenbrand et al. (2013). In turn, Hillenbrand et al. (2013) indicate that when comparing independent $T_{\text{eff}}$ values, the scatter was larger between spectroscopically derived parameters compared to narrowband values. Our results here therefore suggest that also our APOGEE $T_{\text{eff}}$ are more accurate than moderate-resolution optical spectra in the M-type mass range.

Finally, Figure 4 compares the $T_{\text{eff}}$ distributions of previously known members with those of unknown membership sources, as well as the total number of APOGEE targets;
the distributions have been normalized at 4400 K. We also report the predicted distribution from a Kroupa (2001) IMF, assuming a 2.5 Myr isochrone from Siess et al. (2000). It is evident that at intermediate temperatures \( T_{\text{eff}} > 5000 \) the sample of sources with unknown memberships is overpopulated relative to the Galactic IMF. Such enhancement of an intermediate-mass star has never been detected, for members, in the region (Da Rio et al. 2010b; Hsu et al. 2013). We thus conclude that in this \( T_{\text{eff}} \) range, sources without confirmed memberships are mostly field contaminants, likely low- and intermediate-mass dwarfs. At lower \( T_{\text{eff}} \), the very low mass field dwarfs will likely be too faint to contribute a significant contamination to our sample. It is also noteworthy that even the subsample of known members shows a somewhat excessive number of sources at warmer temperatures compared to what is expected from a standard IMF. This is due to an incompleteness bias, in that members with lower \( T_{\text{eff}} \) and higher \( A_V \) will be more likely excluded from our sample because of our targeting luminosity threshold \((H < 12.5)\).

3.2. Extinction

We derived the extinction of our IN-SYNC targets from the knowledge of \( T_{\text{eff}} \) and the observed colors. Specifically, we compared the sources’ observed \((J - H)\) colors with the intrinsic ones from the 2.5 Myr old semiempirical isochrone from Bell et al. (2014), obtained applying an empirical correction to the PISA models (Tognelli et al. 2012) as converted into magnitudes assuming BT-Settl (Allard et al. 2011) synthetic spectra. To convert the reddening excess \( E(J - H) / A_V \) we assumed the reddening curve from Cardelli et al. (1989) for a reddening parameter \( R_V = 3.1 \) or 5.5. We compared our derived \( A_V \) with values from the literature (Da Rio et al. 2012; Fang et al. 2013; Hillenbrand et al. 2013), which were all derived assuming the Galactic \( R_V = 3.1 \). This comparison is shown in Figure 5, where the left panel shows that our APOGEE \( A_V \) values deviate systematically from the optically derived ones. Given the different wavelength ranges adopted to measure the reddening, this could indicate that a different reddening law is required. We thus corrected the literature extinctions as if they had been computed assuming \( R_V = 5.5 \). This was accomplished considering the different color excesses used in each of those works to obtain \( A_V = E(V - I) \) for Hillenbrand (1997), Hillenbrand et al. (2013), and Da Rio et al. (2010b), \( E(7500 \text{ Å} - I) \) for the sources with medium-band photometry from Da Rio et al. (2012), and a combination of SDSS \textit{griz} and 2MASS \textit{JHK} bands for L1641 sources in Fang et al. (2013), for which we adopted a wavelength range represented by the color term \((i - J)\). Figure 5, right panel, confirms that assuming \( R_V = 5.5 \) allows the different \( A_V \) estimates to be in better agreement. From the left panel of Figure 5 it appears that, for the sources in L1641, the discrepancy between APOGEE and literature values of \( A_V \) is more moderate compared to that of the ONC sources. This is because \( A_V \) was estimated from the SED at longer wavelengths and thus less sensitive to changes in the reddening law than in the optical. Because of this, their correction needed in the assumption of \( R_V = 5.5 \) (Figure 5, right panel) is more modest.

Another possibility for the discrepancy in \( A_V \) values assuming \( R_V = 3.1 \) may be the contribution to the \( JH \) photometry from disk emission. This emission would increase the \((J - H)\) color term, leading us to overestimate the stellar reddening. We thus compared the distribution of sources in the diagram of Figure 5 for different ranges of \((K - 8 \mu \text{m})\) infrared slopes, but found no dependence at all on the infrared slope. Thus, we concluded that NIR disk excess emission does not bias our \( A_V \) estimates.

An increase of \( R_V \) compared to the average Galactic value in star-forming regions at increasing densities, indicating grain growth, is not surprising and has been reported before (Johnson 1968; Costero & Peimbert 1970; McCall 2004; Keto & Caselli 2008; Foster et al. 2013; De Marchi & Panagia 2014). In the ONC, however, Da Rio et al. (2010b) found \( R_V = 3.1 \) more suitable to reproduce the distribution of sources in the \( BVI \) two-
A color diagram for the lightly embedded sources surveyed in that study ($A_V < 5$). It is thus likely that the reddening parameter increases along the line of sight, from near Galactic values at the edge of the system to larger grains at higher optical depth. This is consistent with the fact that the volume density of molecular material, at least in the ONC (Da Rio et al. 2014b), increases along the line of sight, with most of the mass and density concentrated at the far end of the stellar cluster. Thus, the more heavily embedded members, which are affected by a flatter reddening law, are engulfed in denser molecular material than the lightly embedded population.

### 3.3. Surface Gravity

Figure 6 shows the surface gravity $\log g$ versus $T_{\text{eff}}$ plot for all our targets, highlighting previously known members from different indicators in the literature. These include HRD position membership from Da Rio et al. (2012), X-ray sources (Getman et al. 2005), IR-excess sources (Megeath et al. 2012), and sources showing either undepleted lithium or Hα excess (Fang et al. 2009, 2013; Hsu et al. 2012). Most of the known members have cool $T_{\text{eff}}$, as expected from the IMF peaking in the very low mass star range. The $\log g$ values are lower than those predicted from dwarfs, compatible with a PMS status of the sources. Although the diagram shows systematic departures from the expected locus, indicated, for example, by the Siess et al. (2000) 2.5 Myr isochrone that best fits the ONC in the HRD, our Paper I has already shown that relative cluster ages are well detected from APOGEE-derived $\log g$ as an increasing sequence from NGC 1333, to IC 348, to the Pleiades.

Overall, the $\log g-T_{\text{eff}}$ sequence for known Orion members remains relatively tight for below 4500 K, with a standard deviation of the order of 0.5 dex. The scatter, for both candidate members and unknown sources, increases at hotter temperature, consistent with the overall poorer performance of APOGEE in this regime (see also Section 3.1).

A clear diagonal feature, composed by sources without confirmed membership, is evident in Figure 6 extending from the upper left ($T_{\text{eff}} \sim 2500$ K and $\log g \sim 2$) to $T_{\text{eff}} \sim 5000$ K and $\log g \sim 4$, where it begins to blend with the field population. Although poorly matched by evolutionary model
prediction, we safely identify it as a red giant branch (RGB) of contaminating field sources. Additional field sources may be located at low $T$ at high surface gravities typical of main-sequence dwarfs. Finally, at intermediate $T_{\text{eff}}$ the large majority of sources with no membership estimates show high log $g$ values, consistent with being mostly field dwarfs, as already discussed in Section 3.1.

3.4. Radial Velocity

Figure 7 shows a comparison of our APOGEE-derived radial velocities $v_r$ in the local standard of rest, with similar values derived by Tobin et al. (2009) from optical spectroscopy of a $\sim 2^\circ$ FOV, for $\sim 750$ sources in both catalogs. Overall the agreement is good, with no noticeable zero-point offsets. The residual scatter may be due to observational errors in both measurements, as well as $v_r$ variations from stellar multiplicity. One feature in Figure 7 is a modest population of data points ($\sim 8\%$) for which our $v_r$ are in line with the majority of the cluster members ($5 \text{ km s}^{-1} \leq v_r \leq 15 \text{ km s}^{-1}$), whereas the measurements from Tobin et al. (2009) appear somewhat lower. As the right panel of Figure 7 shows, the optical $v_r$ distribution is somewhat asymmetric, with the blue tail more prominent than the red one. On the other hand, the APOGEE $v_r$ distribution in the top panel of Figure 7 does not present this skewness. This suggests that a few $v_r$ values measured by Tobin et al. (2009) had been underestimated. These few discrepant sources turn out to be nearly all in the low end of the temperature scale, with $T_{\text{eff}} < 4000$ K. One possibility is that previous results were affected by systematics in the M-type spectral range, possibly owing to inaccurate model spectra used to estimate $v_r$. Some of these sources have a moderately higher $A_V$ than average, and, together with their low $T_{\text{eff}}$, they occupy the faint end of the targeted sample. The observations of Tobin et al. (2009) were conducted during an epoch with a negative heliocentric correction for Orion and in bright time. Thus, low S/N and residual moonlight might have led to underestimated velocities.

A full analysis of the radial velocity distribution, in order to assess the kinematic status of the young stellar population throughout the Orion A cloud, will be presented in a separate, forthcoming paper (N. Da Rio et al. 2016, in preparation).

4. STELLAR AGES

The determination of stellar ages in young stellar clusters is exceptionally valuable for the study of star formation, as well as for planet formation, e.g., providing constraints to the circumstellar disk lifetimes. Spatial variations in ages along a molecular cloud are the footprints of how star formation progressed throughout space and time. Similarly, the detection of a genuine spread in ages traces the duration of the star formation process, helping to constrain theoretical models and improve our understanding on the timescales for conversion of gas into stars (Elmegreen 2000; Hartmann et al. 2001; Tan et al. 2006; Huff & Stahler 2007; Longmore et al. 2014).

Yet, determining ages of young stars is known to be quite problematic (see Soderblom et al. 2014, for a review). This is due to the difficulty in extracting their stellar parameters—owing to their complex spectra, variability and differential extinction (Da Rio et al. 2010a, 2010b), unresolved multiplicity, binary evolution, and the fact that PMS evolution may be affected by the protostellar accretion history (Baraffe et al. 2009, 2012). However, this last issue may not be dominant (Hosekawa et al. 2011). These limitations have put the reality of the age spreads, measured from the broadening of the PMS sequence of young clusters’ HRDs, into question. On one hand, young clusters are observed to be unembedded already at very young ages (2 Myr; Portegies Zwart et al. 2010; Longmore et al. 2014), which limits the duration of ongoing star formation. On the other hand, very fast star formation scenarios are also problematic (Tan et al. 2006). Several studies have been carried out to characterize the age distribution in the ONC: Reggiani et al. (2011) showed that observational uncertainties in the construction of the HRD are minimal; Jeffries et al. (2011), from the lack of correlation between the fraction of stars bearing disks and their isochronal ages, concluded that the intrinsic width of the ONC’s age distribution is less than half of the apparent width in logarithmic scale. Finally, Da Rio et al. (2014a) showed that a real age spread of at least 0.2 dex in the ONC (95% of the population with ages between 1 and 6 Myr) must be invoked to justify the observed correlation between measured mass accretion rates and ages. To summarize, studies have shown that isochronal ages remain very uncertain, but this does not invalidate the existence of age spreads in young star-forming regions, including Orion. With all these caveats in mind, we attempt to study the age distribution in the Orion A cloud.

4.1. New Evidence for a Spread in Stellar Ages

Figure 8 shows the HRD of the entire Orion A cloud survey: the luminosity has been derived from dereddened $J$ magnitudes, adopting our extinctions (Section 3.2) and corrected adopting the bolometric corrections from Bell et al. (2014). Isochrones from Siess et al. (2000) are also shown. We assigned ages to each source adopting these models in two ways: interpolating the models into the HRD, and in the log $g$–$T_{\text{eff}}$ plane. The latter case, as shown in Figure 6,
affected by systematic uncertainties. Although these systematics depend on $T_{\text{eff}}$ and are likely nonlinear, we correct the surface gravity ages by a constant shift of 0.64 dex, which is the mean of the difference between all the ages according to the two methods. The comparison of the corrected ages from $g_{\log}$ and $T_{\text{eff}}$ is shown in Figure 9, left panel, limited to known members and sources with $T_{\text{eff}} < 4200$ K, to avoid the poor accuracy in the stellar parameters at higher temperatures. Despite a scatter larger than the nominal average error bars, the correlation between the two is clear, with a measured Pearson correlation coefficient of $\rho \sim 0.35$. Using a permutation test, we have established this correlation to be highly significant to a $\sim 11\sigma$ level. By comparing the scatter along the diagonal line in Figure 9 with that along its normal (indicative of anticorrelation), both weighted on the error bars of each point, we concluded that such correlation is indicative of an age spread of $0.16 \pm 0.01$ dex. This is smaller than the age spread estimated in the ONC (0.2 dex; Da Rio et al. 2014a or even 0.35 dex accounting only for HRD uncertainties; Reggiani et al. 2011), but it is only a lower limit. This is due to the fact
that systematic offsets in the estimated ages using an independent method may vary across different regions of the stellar parameter space. This is evident from the right panel of Figure 9, in which sources are color-coded according to their $T_{\text{eff}}$: a clear gradient is evident, with age from $\log g$ being systematically underestimated for cool stars, and vice versa. Overall, the measured apparent isochronal age spread is $\sim 0.4$ dex, when measured locally given the age gradients along the Orion A filament (see Section 4.2). This is identical to that measured in the ONC from other studies (Hillenbrand 1997; Da Rio et al. 2012). We must highlight that this spread in ages identifies solely, strictly speaking, a spread in stellar radii, which may or may not indicate an age spread (Jeffries et al. 2011; Baraffe et al. 2012). This is because stellar evolutionary effects due to the past accretion history can potentially influence the radius of a PMS star for a given mass and age. As discussed in Da Rio et al. (2014a), however, the relation between mass accretion rates and isochronal ages implies a lower limit for the true age spread of $\sim 0.2$ dex, corresponding, in the ONC, to the formation of 95% of the stars within 5 Myr. Since the apparent spread in age we measure appears to be roughly constant throughout the entire cloud, we suggest that such relatively long duration of star formation occurred in the entire region. We stress, however, that given our lack of knowledge on the 3D structure of the cloud, part of this overall spread could be due to an age spread along the line of sight. This, however, is negligible at least in the ONC; the bulk of the unembedded population, likely distributed a few parsecs along the line of sight, shows evidence of a large spread in stellar ages. In Paper I we also found evidence for a highly significant spread in stellar radii in IC 348, based on APOGEE-derived surface gravities and isochronal ages.

We then utilize other indicators to better understand its nature. In Figure 10, left panel, we report the relation between $A_V$ and HRD ages, limiting to known members and highlighting sources with small uncertainty in ages with darker symbols. It appears that whereas young sources are distributed in a range of optical depths within the cloud, older members are basically found only at very low $A_V$, i.e., on the foreground end of the stellar distribution along the line of sight. This trend, however, is potentially suffering from two biases. First, if the extinction of a source had been highly overestimated, then so would its extinction-corrected $\log L$, and thus its age underestimated; vice versa for underestimated $A_V$. Thus, errors in extinction tend to move sources in the $A_V$-age plane diagonally, in the same direction of the correlation observed. We exclude this bias from playing a significant role here, because the correlation persists when we restrict to sources with minimal age (and thus $A_V$) errors (black circles in Figure 10, left panel) and also because of the good agreement between our APOGEE-derived $A_V$ and values from the literature (Figure 5). A second bias could originate from incompleteness: older PMS stars are fainter than young ones, and the heavily embedded ones will be likely too faint to be included in our sample. We tested this scenario isolating known members at intermediate temperatures ($T_{\text{eff}} > 4500$ K), where incompleteness is quite low compared to the cold end of the population, and found that the correlation $A_V$-age remains identical. We therefore conclude that indeed older stars are slightly in foreground, whereas younger stars may be more embedded in the molecular material. This is not surprising considering that there is evidence that the majority of the molecular material, at least in the ONC, is located behind the majority of the population along the line of sight (see da Rio et al. 2014b). Within this material, dense cores are known to form stars today (Prisinzano et al. 2008).

We also look for correlation between the isochronal ages and the circumstellar environment properties. In Figure 10, right panel, we plot the infrared slope ($K_s - 8 \mu m$), from 2MASS and SPITZER/IRAC, respectively, with respect to stellar ages, again limiting to known members. We clearly observe that sources with steeper slopes, indicative of earlier stages of stellar evolution, appear to have systematically younger ages derived from the HRD. This fact also corroborates the fact that the spread in stellar radii is in fact indicative of the presence of genuine age spread, although the actual magnitude of this spread cannot be accurately constrained from this analysis.

Using the ($K - 8 \mu m$)-age data, we can estimate the disk timescales. For simplicity we assume that the ratio of disk-bearing sources, in a given age interval of our target sample, is
the ratio between the number of sources with 
\((K - 8 \mu m) > 1\) mag and the total number. Limiting to known 
members with \(T_{\text{eff}} < 4200\) K as in Figure 10, we determine an 
e-folding timescale for disk removal of \(2.7 \pm 0.4\) Myr, 
consistent with previous findings (Fedele et al. 2010). We also 
note that restricting to the ONC, the timescale increases, 
indicating weaker correlations between apparent age and disk 
properties, reaching up to 6 Myr within a radius of \(0.5\) from 
the trapezium and 10 Myr within \(0.25\). All these timescales, 
however, remain upper limits, as they are derived from the 
apparent measured ages. This is because when fitting the disk 
fractions versus ages, additional scatter on the x-axis flattens 
the shape of the fitted function—in this case an exponential—
because of regression dilution. It should also be noted that in 
the densest core of the ONC, other dispersal mechanisms may 
affect the disk fraction, such as photoevaporation (Scally & 
Clarke 2001; Robberto et al. 2002; Adams et al. 2004) or 
dynamical truncation (de Juan Ovelar et al. 2012; Rosotti et al. 
2014), although the latter mostly affects the external disk 
radius, and not the inner disk emission.

4.2. Spatial Variations of Stellar Ages

We look for systematic spatial variations of stellar ages 
along the Orion A cloud. Given the physical size of the cloud, 
about 40 pc assuming a distance of 414 pc, and the young age 
of the system, there has been no time for a dynamical 
communication between the two ends of the filament, and thus 
no guarantee that the young population shares the same age 
throughout it. In Figure 11 we plot the stellar ages and their 
local mean, as a function of declination. Whereas no large-scale 
age gradients are detected, we find a statistically significant 
older age for the population at \(\delta \approx -6.2\), where the members 
are about 50% older than, e.g., in the ONC (\(\delta \approx -5.5\)).

4.3. Is NGC 1980 a Foreground Cluster?

Following on the localized increase in stellar clusters just 
mentioned, we note that a similar result was already presented 
in the literature. Alves & Bouy (2012) suggested that the young 
population in the vicinity of \(\iota\) Ori, identified with the 
association NGC 1980, is in fact a separate population 
unrelated to the Orion A filament. Their claim was based on 
noticing that the majority of such sources are affected by very 
little extinction, thus possibly older (4–5 Myr old), and located 
in the foreground with respect to the rest of the region. Later 
Bouy et al. (2014) used a multiband photometric approach to 
isolate candidates of this population, confirmed its older age, 
and estimated a distance to this system of \(\sim 380\) pc, more than 
30 pc closer to us than the rest of the young population. We 
investigate these claims further based on our APOGEE data. 
We cross-match the catalogs from Bouy et al. (2014) 
with our sample and consider all sources present in both these 
samples. Among these, we further distinguish stars attributed 
as “foreground” with a probability \(p > 70\%\) from Bouy et al. 
(2014) from the remaining, which we refer to as “nonforeground.” 
Figure 12 shows the spatial distribution of these samples. The candidate population is indeed centered to the 
south of the ONC but is poorly concentrated and very 
spread out.

Figure 13 shows the cumulative distributions of the 
APoGEE-derived \(A_V\) values for sources in these different 
samples. All the sources in the Bouy et al. (2014) sample 
match closely the reddening distribution of our APOGEE 
survey. We confirm that the candidate foreground population is 
predominantly composed by low-\(A_V\) sources, in line with the 
conclusion of their work. We also confirm that these sources 
possess an older characteristic age: again, whereas the overall 
age, as derived both from our HRD and from the \(\log g-T_{\text{eff}}\) 
plane, of the entire Bouy et al. (2014) catalog matches closely 
that of our survey, the candidate foreground population is 
\(\sim 40\%\) older than the candidate nonforeground. This is also
understandable considering that the candidate foreground population is centered at declinations \(-6.5 \leq \delta \leq -6\), where the overall age of the Orion A cloud appears systematically older (see Figure 11).

We further analyze other indicators of age from the literature. We consider the H\(\alpha\) equivalent width (EW) estimates of Fang et al. (2013), which were derived from optical spectroscopy, for all sources matching both our APOGEE sample and that of Bouy et al. (2014), and restrict the sample in a declination range \(-7^\circ < \delta < -5^\circ 30'\), in order to bracket more closely the area around NGC 1980. We separate classical T Tauri sources (CTTs) as those showing EW > 20 \text{ Å} from the remaining weak-line T-Tauri stars (WTTSs). Table 2 reports the numbers in the different stellar samples. The sample from Bouy et al. (2014) matches all sources in our APOGEE survey within the declination range we considered. The candidate “foreground” population, however, shows a sixfold excess in the WTTS/CTTS ratio compared to the remaining “nonforeground,” although this difference is statistically significant only at \(\sim 1.8\sigma\) owing to the low numbers of sources included. This finding further supports the older age of the candidate “foreground” sources. Similarly, we consider the disk classification from Fang et al. (2013), which, based on infrared SEDs, separates sources bearing thick disks, thin disks, transition disks, or diskless members. Table 3 reports the numbers in each category for the different stellar samples. Again, the candidate “foreground” population shows a larger fractional excess of transition disks and diskless stars compared to the “nonforeground” sample, confirming a more evolved population.

We have confirmed that the proposed “foreground” population isolated by Bouy et al. (2014) is indeed both older and affected by less extinction. We now analyze its kinematic properties. Figure 14, left panel, reports the position–\(v_r\) diagram for the declination range around NGC 1980. For APOGEE targets observed in more than one epoch we have considered a weighted mean of the individual \(v_r\) values. Since the entire Orion A cloud presents a large-scale gradient in \(v_r\) from north to south, observed both in the gas kinematics (Bally et al. 1987; Nishimura et al. 2015) and in the stellar motions (Tobin et al. 2009, N. Da Rio et al. 2016, in preparation), we isolated this gradient using a linear regression and extracted the residuals \(\Delta v_r\) for each source with respect to the mean velocity at each declination. Figure 14, right panel, reports both the \(v_r\) distribution of the residuals and the cumulative distribution. We caution the reader that such distributions are not corrected for \(v_r\) uncertainties and scatter from multiplicity; a full kinematic analysis throughout the region is to be presented in Da Rio et al. (2016, in preparation); however, this is sufficient for a meaningful comparison between the different samples. We excluded from the analysis stars with \(v_r\) residuals larger than 20 km s\(^{-1}\) as outliers. Although the mean \(v_r\) show some small offsets between the different samples, with the candidate “foreground population” slightly blueshifted compared to the “nonforeground” sample, the distributions appear very similar. A K-S test on the cumulative distributions could not reject the hypothesis that the \(v_r\) distributions of the foreground and nonforeground populations are identical, with high significance (\(p < 10^{-6}\)).

Given that the kinematic properties of the candidate foreground cluster proposed by Alves & Bouy (2012) and Bouy et al. (2014) are indistinguishable from those of the rest of the population at the same position in the sky, we find it unlikely that this population is a separate entity from the rest of the Orion A young population and located tens of parsecs closer along the line of sight. Instead, we find it more likely that such a population simply represents the older tail of the age distribution around \(\delta \sim 6^\circ\), in the context of a long-duration star formation event. Our proposed scenario mainly leverages on the kinematic evidence. The entire Orion A cloud shows a \(v_r\) gradient of 10 km s\(^{-1}\), with the north end receding and the south end approaching. If the foreground population were separated by several tens of parsecs, which is about the size of the Orion A cloud itself, it would be very coincidental for it to share an identical mean \(v_r\) to the portion of the younger Orion A population behind it. This would make the specific direction of the line of sight somewhat special: on one hand because the foreground population would be perfectly aligned in projection against the Orion A filament, and on the other hand if an observer had to look at it from a slightly different angle, its mean \(v_r\) (and possibly the \(v_r\) dispersion) would not match that of another portion of the young population seen in its background. We do not exclude that the older populations remain somewhat in the foreground of the Orion A cloud, but it seems likely that any separation between the two should be minimal, and the hypothesis that it originates from an independent star formation event would be unfavorable. Also, the low \(A_V\) of the older population may not necessarily imply a

| Table 2 | T Tauri Star Classification within \(-7^\circ < \delta < -5^\circ 30'\) |
|---------|-------------------|
| Sample  | CCTS | WTTS | Unknown | WTTS/CTTS |
| All sources | 44  | 122  | 596  | 2.8 ± 0.5  |
| All in B14 | 26  | 80  | 275  | 3.1 ± 0.7  |
| B14 “foreground” | 5  | 46  | 93   | 9.2 ± 4.3  |
| B14 “nonforeground” | 21 | 34  | 182  | 1.6 ± 0.4  |

| Table 3 | Disk Properties within \(-7^\circ < \delta < -5^\circ 30'\) |
|---------|-------------------|
| Sample  | Thick | Thin | Trans. | No Disk | Unknown |
| All sources | 45  | 3  | 14  | 105  | 595  |
| All in B14 | 28  | 1  | 11  | 67   | 247  |
| B14 “foreground” | 6  | 0  | 7   | 38   | 93   |
| B14 “nonforeground” | 22 | 1  | 4   | 29   | 181  |
closer distance to us, but simply a lower density of molecular material surrounding it, which is expected for a more evolved young population. Thus, we speculate that star formation in the Orion A cloud—which developed over several Myr in each location—peaked earlier in the region around NGC 1980, and later in the remaining areas.

5. MEMBERSHIPS

Based on all data and parameters we collected from our APOGEE spectra, we can improve membership determination for all sources with no membership derived in the literature. Specifically, we consider the location of all the sources in a number of planes: (a) the CMD $H-(J-H)$, (b) the HRD, (c) the log $g$-$T_{\text{eff}}$ plane, and (d) the position–velocity plane $v_r$-$\delta$.

For the first three cases, it is evident from Figures 2, 8, and 6 that known members tend to occupy well-confined regions of these planes. In the CMD they are confined to a locus that is redder than a young PMS isochrone, whereas MS contaminants have bluer colors. In the HRD and $T_{\text{eff}}$-$\log g$ planes at low $T_{\text{eff}}$ ($<5000$ K) known members occupy a tighter sequence compared to the rest of the unclassified sources. At hotter temperatures $T_{\text{eff}}$, log $L$, and log $g$ have little to no diagnostic power to isolate members, but as anticipated, the large number of sources in this range suggests that the vast majority of them are nonmembers.

For every star, in each of these three planes we consider the 50 closest sources to the considered star, where the distance is measured in units of measurement errors in the two parameters of the plane. We then count among the 50 sources the fraction that have been previously identified as members, and we consider this value, regardless of our knowledge of the membership from the literature, a basic indicator of the membership probability for the selected star in that given plane. We refer to these three quantities as $p_{\text{HRD}}$, $p_{\log g}$, and $p_{\text{CMD}}$. Figure 15 shows the three planes, with sources color-coded according to the value of $p$ for each specific plane.

Figure 14 compares $p_{\text{HRD}}$ with $p_{\log g}$. A clear correlation is evident, and two populations appear separated at high and low membership probability. Moreover, known members from the literature show high values of $p$, whereas sources without a literature membership are mostly distributed in the low-$p$ end of this diagram. A few sources with no previous memberships still populate the top right corner, and among these some could be new actual members. On the other hand, some known members show very low membership probability from these two planes, and these are all intermediate-$T_{\text{eff}}$ stars. A similar comparison using $p_{\text{CMD}}$ estimates shows much less correlation with the other two, owing to the ability of this plane to only identify low-$A_V$ field contaminants as systematically bluer than members in $J-H$.

Finally, we consider the radial velocity distribution of all the sources, compared to the average one of the known members. Given the large-scale gradients of the mean velocity along the filament, which is also observed in the gas (Bally et al. 1987; Nishimura et al. 2015), we construct a two-dimensional map of the average $v_r$ and the velocity dispersion considering the known members. To this end, for each point in R.A. and decl. of our FOV, we consider a circular aperture of 20' radius. If this contains at least 30 members, we measure their $v_r$ and $\sigma$, weighting on the errors and excluding outliers with a sigma clipping algorithm ($\sigma > 3$). Note that for this application the local $\sigma$ was not corrected for unresolved multiplicity. A full analysis of the stellar velocity dispersion throughout the Orion A cloud is to be presented in a forthcoming paper. For each star, we then computed the velocity offsets $\Delta v_r$, in units of standard deviations, from the local $\overline{v_r}(\alpha, \delta)$, where the standard deviation comprises the measurement error in $\delta v_r$, the local $\sigma_r$, and the scatter in the individual measurements of $v_r$ for the star, if observed in more than one epoch and larger $\delta v_r$, which is the case of, e.g., $v_r$ variations from binarity.

From all $p_{\text{HRD}}$, $p_{\log g}$, and $p_{\text{CMD}}$, and $\Delta v_r$ for all our targets, we attempt to estimate memberships for sources with no
membership estimates from the literature. A rigorous approach that utilizes these four parameters as formal probabilities cannot be applied, since none of them is a probability, but they represent arbitrary parameters with variable diagnostic ability to trace membership in the parameter space. For instance, \( p_{\text{HRD}} \), \( p_{\log g} \), and \( p_{\text{CMD}} \) are not fully independent from each other, since positions in the HRD and in the CMD are related for less than the differential extinction. Also, \( \log g \) and \( \log L \) are correlated for any given temperature. As anticipated, \( p_{\text{HRD}} \) and \( p_{\log g} \) have little diagnostic power for the hotter sources, because this \( T_{\text{eff}} \) range is dominated by contaminants. Therefore, we look for the optimal, while arbitrary, combination of constraints that reasonably maximize the number of new candidate members we identify while safely reducing the number of false candidates. A good combination of criteria must recover, as candidate members, the largest number of known members from the literature, while also maximizing the number of new candidates previously uncategorized.

For sources with \( T_{\text{eff}} > 5000 \) K we simply impose that the \( v_r < 2.5 \), i.e., within the 99\% percentile of the local mean stellar velocity, and also impose \( p_{\text{CMD}} > 0.3 \), to exclude MS sources bluer than the PMS sequence of the young population. For the colder end of the population (\( T_{\text{eff}} < 5000 \) K), where both the HRD and the \( T_{\text{eff}}-\log g \) planes allow us to separate well PMS stars from contaminants, we impose, in addition to the constraints for hotter sources, also \( p_{\text{HRD}} + p_{\log g} > 0.8 \), i.e., above the dashed line in Figure 16. With these constraints we were able to recover 95\% of the known members. The remaining 120 known members were not selected primarily as a result of discrepant \( v_r \) (101 sources), likely due to binarity. In addition, our membership criterion selected 383 new sources as candidate members. Figures 17 and 18 show the new candidate members in the same planes explored before.

As evident also from Figure 18, the new identified candidate members are mostly in the cool end of the \( T_{\text{eff}} \) scale, with 75\% of them with \( T_{\text{eff}} < 5000 \) K. Moreover, nearly all of them appear to be class III sources, with 95\% of them showing an IR slope (\( K-8 \mu m < 1 \)). This is visible in all panels of Figure 18: new cool candidates tend to show lower luminosities and higher \( \log g \) compared to the mean of the known members, while their location in these panels is in agreement with the overall population. The 25\% of the new candidate members with \( T_{\text{eff}} > 5000 \) K have been mostly identified through their \( v_r \). Figure 19 shows the distribution of these in the surveyed area. The largest concentrations of new members are located on the ONC flanking fields, north of the ONC, and in the southernmost end of L1641-south. This is not surprising because in these areas there are no spectroscopic or X-ray surveys, and the sole membership indicator from previous literature studies is the IR excess (Megeath et al. 2012). Thus, it is expected that diskless members were not identified by this
study. Similarly, new members are found on the edges of our surveyed area in L1641, because optical studies (Fang et al. 2009, 2013; Hsu et al. 2012, 2013), as well as X-ray observations (Pillitteri et al. 2013), had a narrower FOV along the filament.

We must highlight that the sample of new candidate members is not unbiased, as it originated from a method based on the previously known members, which is a heterogenous sample. Moreover, the method itself is not consistently reliable, as the ability to assign membership strongly depends on temperature. Thus, our membership estimation should be considered as a list of new “candidates” rather than a list of new “confirmed members.”

6. SUMMARY

Within the SDSS-III IN-SYNC survey, we have targeted the young stellar population of the Orion A molecular cloud with the APOGEE spectrograph. We have obtained high-resolution H-band spectra for nearly 2700 individual sources, chosen among known members but also targeting sources of unknown membership. We extract stellar parameters ($T_{\text{eff}}$, log $g$, $v \sin i$, $A_V$) and radial velocities $v_r$ adopting a fitting procedure on grids of synthetic spectra. Consistent with the previous IN-SYNC surveys in the Perseus Cloud (Cottaar et al. 2014, 2015; Foster et al. 2015), we find that the stellar parameters extracted from the APOGEE spectra are in good agreement with literature values from optical studies, especially at low $T_{\text{eff}}$ ($\lesssim$4000 K).
Tables 4 and 5 report our estimated stellar parameters and membership estimates. Our main results can be summarized as follows.

1. By comparing our $A_V$ estimates, derived for individual stars from the color excess $E(J - H)$ with respect to the intrinsic $(J - H)_0$ at a given $T_{\text{eff}}$ with literature $A_V$ from optical spectroscopy, we find that a reddening law compatible with $R_V = 5.5$ is better suited to reproduce the data than a diffuse interstellar medium reddening law. Given that, at low $A_V$, $R_V = 3.1$ was found to be adequate (Da Rio et al. 2010a), we conclude that grain growth is present at an increasing level of embeddedness, where in Orion also the volume density of gas increases.

2. We study the age spread throughout the region and find evidence for a large spread in stellar ages. We find a clear correlation between ages assigned from isochrones in the HRD and ages derived in the log $g$–$T_{\text{eff}}$ plane, indicating that, at least, a large spread in stellar radii is real. We also detect a clear trend between estimated ages and $A_V$, in that the oldest tail of the population is systematically unembedded. This may indicate progressive star formation along the line of sight, consistent with the fact that ongoing star formation in the region, associated with the dense gas, is located behind the PMS population.

3. We study the foreground population candidate members, located in the region of NGC 1980 and $\iota$ Ori proposed by Alves & Bouy (2012) and Bouy et al. (2014). Based on our data, we confirm that this population is older than the rest of the population by about 40% and less embedded. Moreover, in this declination range there is a significant underabundance of young (< 1 Myr) stars, suggesting that star formation occurred here earlier than in the rest of the cloud. However, we suggest that this population is not completely separate from the filament and that it would be unlikely for it to be located many parsecs in foreground, given that the kinematic properties ($\nu_\sigma$) appear identical to those of the younger, embedded members in the same region and show no discontinuity with the kinematic gradient of the entire Orion A cloud.

4. Based on a combination of constraints considering stellar parameters ($T_{\text{eff}}$, log $L$, log $g$), NIR photometry, and radial velocities, we identify 383 new candidate members. These are mostly located in areas of our FOV with no previous spectroscopic or X-ray coverage and are mostly diskless PMS sources that could not be identified as...
