WIYN OPEN CLUSTER STUDY. XXXVIII. STELLAR RADIAL VELOCITIES IN THE YOUNG OPEN CLUSTER M35 (NGC 2168)

Aaron M. Geller\textsuperscript{1,3}, Robert D. Mathieu\textsuperscript{1,3}, Ella K. Braden\textsuperscript{1,3}, Søren Meibom\textsuperscript{1,3,4}, Imants Platais\textsuperscript{2}, and Christopher J. Dolan\textsuperscript{1,3}

\textsuperscript{1} Department of Astronomy, University of Wisconsin—Madison, WI 53706, USA; geller@astro.wisc.edu, mathieu@astro.wisc.edu, braden@physics.wisc.edu, smeibom@cfa.harvard.edu, chris@chrisdolan.net

\textsuperscript{2} Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, MD 21218, USA; imants@pha.jhu.edu

\textsuperscript{3} Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

\textsuperscript{4} Current address: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA.

ABSTRACT

We present 5201 radial-velocity (RV) measurements of 1144 stars as part of an ongoing study of the young (150 Myr) open cluster M35 (NGC 2168). We have observed M35 since 1997, using the Hydra Multi-Object Spectrograph on the WIYN 3.5 m telescope. Our stellar sample covers main-sequence stars over a magnitude range of $13.0 \leq V \leq 16.5$ (1.6–0.8 $M_\odot$) and extends spatially to a radius of 30 arcmin (7 pc in projection at a distance of 805 pc or $\sim 4$ core radii). Due to its youth, M35 provides a sample of late-type stars with a range of rotation periods. Therefore, we analyze the RV measurement precision as a function of the projected rotational velocity. For narrow-lined stars ($v \sin i < 10$ km s$^{-1}$), the RVs have a precision of 0.5 km s$^{-1}$, which degrades to 1.0 km s$^{-1}$ for stars with $v \sin i = 50$ km s$^{-1}$. The RV distribution shows a well-defined cluster peak with a central velocity of $-8.16 \pm 0.05$ km s$^{-1}$, permitting a clean separation of the cluster and field stars. For stars with $\geq 3$ measurements, we derive RV membership probabilities and identify RV variables, finding 360 cluster members, 55 of which show significant RV variability. Using these cluster members, we construct a color–magnitude diagram for our stellar sample cleaned of field star contamination. We also compare the spatial distribution of the single and binary cluster members, finding no evidence for mass segregation in our stellar sample. Accounting for measurement precision, we place an upper limit on the RV dispersion of the cluster of 0.81 $\pm$ 0.08 km s$^{-1}$. After correction for undetected binaries, we derive a true RV dispersion of 0.65 $\pm$ 0.10 km s$^{-1}$.

Key words: binaries: spectroscopic – open clusters and associations: individual (NGC 2168)

Online-only material: machine-readable and VO tables

1. INTRODUCTION

Young open clusters are laboratories for the direct study of the near-primordial characteristics of stellar populations. Their properties, and particularly those of the binary systems, offer unique insights into how stars are born and provide essential information for N-body studies of star clusters. Indeed, with sophisticated N-body simulations now able to model real open clusters (e.g., Hurley et al. 2005), knowledge of the correct initial conditions is all the more important. In particular, the initial binary population has a vast impact on the dynamical evolution of the cluster, and the characteristics of the initial binary population will affect the overall frequency, formation rate, and formation mechanisms of anomalous stars, like blue stragglers, as interactions with binaries are thought to be catalysts for the formation of these exotic objects (Hurley et al. 2005; Knigge et al. 2009). As a rich open cluster with an age of $\sim 150$ Myr, M35 is a prime cluster to define these hitherto poorly known initial conditions for the binary population required for any open cluster simulation.

M35 is a fundamental cluster in the WIYN Open Cluster Study (WOCS; Mathieu 2000), and as such has a strong base of astrometric and photometric observations from both the WOCS collaboration and others. The cluster is centered at $\alpha = 6^h09^m07.5$ and $\delta = +24^\circ20'28''$ (J2000), toward the Galactic anticenter. Numerous photometric studies have identified the rich main-sequence population (e.g., Kalirai et al. 2003; von Hippel et al. 2002; Sung & Bessell 1999). WOCS CCD photometry places the cluster at a distance of 805 $\pm$ 40 pc, with an age of 150 $\pm$ 25 Myr, a metallicity of [Fe/H] $\sim -0.18 \pm 0.05$, and a reddening of $E(B-V) = 0.20 \pm 0.01$ (C. P. Deliyannis 2006, private communication). The most recent published parameters, from Kalirai et al. (2003), place the cluster at a distance of $912^{+70}_{-55}$ pc ($\mu m - M_0 = 9.80 \pm 0.16$) with an age of 180 Myr, adopting a $E(B-V) = 0.20$ and [Fe/H] $= -0.21$ (see Kalirai et al. 2003 for a thorough review of previous photometry references and their derived cluster parameters). We note that these two recent studies used different isochrone families.

There have been multiple proper-motion studies of the cluster (Ebbighausen 1942; Cudworth 1971; McNamara & Sekiguchi 1986a), although none determine cluster membership for individual stars fainter than $V \sim 15.0$. Using proper motions, Leonard & Merritt (1989) derive a cluster mass from 1600 to 3200 $M_\odot$ within 3.75 pc. Detailed observations have also been made in M35 to study tidal evolution in binary stars (Meibom & Mathieu 2005; Meibom et al. 2006, 2007), lithium abundances (Steinhauer & Deliyannis 2004; Barrado y Navascués et al. 2001), and white dwarfs (Reimers & Koester 1988; Williams et al. 2004, 2006, 2009).

This is the first paper in a series studying the dynamical state of M35 through the use of radial-velocity (RV) measurements. The data and results presented in this series will form the largest database of spectroscopic cluster membership and variability in M35 to date. In this paper, we present results from our ongoing
RV study of the cluster, which we began in 1997 September. Our stellar sample includes solar-type main-sequence stars within the magnitude range of 13.0 < \( V < 16.5 \), which corresponds to a mass range\(^5\) of 1.6–0.8 \( M_\odot \). The main-sequence turnoff is at \( V \sim 9.5, \sim 4 M_\odot / 5.\) In Section 2, we describe this stellar sample, observations, and data reduction in detail. We thoroughly investigate our RV measurement precision and the effect of stellar rotation in Section 3. Then, in Section 4, we derive RV membership probabilities, and use our study of the RV precision to identify RV variables, which we assume to be binaries or higher-order systems. Within this mass range, we identify 360 solar-type main-sequence members; 305 are single\(^6\) (non-RV-variable) stars while 55 show significant RV variability. We then use these results to plot a color–magnitude diagram (CMD) cleaned of field star contamination, to search for evidence of mass segregation, and to study the cluster RV dispersion (Section 5). Finally, in Section 6, we provide a brief summary. In future papers, we will study the binary population of M35 in detail, providing observations that will be used to directly constrain the initial binary population of open cluster simulations.

2. OBSERVATIONS AND DATA REDUCTION

In the following section, we define our stellar sample, provide a detailed description of our observations and data-reduction process, and discuss the completeness of our spectroscopic observations.

2.1. Photometric Target Selection

Initially, we created our M35 target list from the stars in three wide-field CCD images centered on M35, taken by T. von Hippel with the Kitt Peak National Observatory (KPNO) Burrell Schmidt telescope on 1993 November 18 and 19. These images have \( V \) exposures of 4 s, 20 s, and 180 s and \( B \) exposures of 4 s, 25 s, and 240 s covering a 17′ × 17′ field. We obtained \( B \) and \( V \) photometry with a limiting magnitude of \( V = 17 \), denoted as source 1 in Table 1. Additionally, we derive astrometry from these plates, tied to the Tycho catalog.

More recently, we added to our database the \( BV \) photometry of C. P. Deliyannis (2006, private communication), taken on the WIYN\(^7\) 0.9 m telescope with the S2KB 2K by 2K CCD. This photometry derives from a mosaic of five fields. Each field has a 20′ × 20′ field of view, with one central field and four tiled around the center, for a total field of view of 40′ × 40′. This photometry is denoted as source 2 in Table 1, and covers 74% of the objects we have observed in this study. We note that this photometry is more precise than that of source 1. The star-by-star difference in \( V \) magnitudes for the two sources is roughly Gaussian with \( \sigma = 0.06 \) mag. However, there is a tail that extends beyond three times this sigma value. Therefore, we caution the reader when using magnitudes from source 1.

We selected stars for the RV master list based on three constraints. The faintest sources that can be observed efficiently at echelle resolution using the Hydra Multi-Object Spectrograph (MOS) on the WIYN 3.5 m have \( V = 16.5 \); this therefore sets our faint limit for observations. Stars bluer than \((B - V) < 0.6 \) do not provide precise RV measurements due to rapid rotation and paucity of spectral lines; this therefore sets our blue limit for observations. Finally, we perform a photometric selection of cluster member candidates, shown as the outlined region\(^8\) in Figure 1. This region includes a wide swath above the main sequence so as to not select against binary stars (e.g., Dabrowski & Beardsley 1977), yet also removes stars that are very likely cluster non-members. This photometric selection allows for an efficient survey of the cluster. Our sample extends radially to 30 arcmin from the cluster center. At a distance of 805 pc, this corresponds to the inner \( \sim 7 \) pc of the cluster in projection. Given the core radius derived by Mathieu (1983) of 1.9 ± 0.1 pc, our sample is drawn from the inner \( \sim 4 \) core radii.

Note that we lack \( BV \) photometry for \( \sim 11\% \) of the point sources found within 30 arcmin from the cluster center in the Two Micron All Sky Survey (2MASS). For most of these objects, it is likely that there is a nearby or overlapping

\(^5\) This mass range is derived from a 180 Myr Padova isochrone (Marigo et al. 2008) using the distance, reddening, and metallicity from Kalirai et al. (2003).

\(^6\) In the following, we use the term “single” to identify stars with no significant RV variation. Certainly, many of these stars are also binaries, although generally with longer periods and/or lower mass ratios \( q = \frac{m_2}{m_1} \) than the binaries identified in this study. When applicable, we have attempted to reduce this binary contamination amongst the single-star sample by photometrically identifying objects as binaries that lie well above the single-star main sequence (see Section 4.2).

\(^7\) The WIYN Observatory is a joint facility of the University of Wisconsin—Madison, Indiana University, Yale University, and the National Optical Astronomy Observatory (NOAO).

\(^8\) Specifically, we select stars with\( 0.6 < (B - V) < 1.5, 13.0 < V < 16.5 \) and between the lines defined by \( 5.7 (B - V) + 8.6 < V < 5.7 (B - V) + 11.0 \).
additional object that has prevented accurate $BV$ photometric measurements from either of our sources. These objects, by default, are not included in our stellar sample. In total, our stellar sample contains 1344 stars.

2.2. Spectroscopic Observations

Since 1997 September, we have collected 5201 spectra of 1144 stars within this stellar sample as part of an ongoing observing program using the WIYN Hydra MOS. For the majority of these observations, we use Hydra’s blue-sensitive 300 μm fibers, which project to a 3:1 aperture on the sky. We use the 316 lines mm$^{-1}$ echelle grating, isolating the 11th order with the X14 filter. The resulting spectra span a wavelength range of $\sim$25 nm, with a dispersion of 0.015 nm pixel$^{-1}$, centered on 512.5 nm. We have also occasionally centered our observation on 637.5 nm using a very similar setup. In this region, we use the same grating, but isolate the ninth order with the X18 filter. These observations span a slightly larger wavelength range of $\sim$30 nm, and have a dispersion of 0.017 nm pixel$^{-1}$. Due to a broken filter, observations taken after the spring of 2008 use different observing setups than discussed above; most are centered on 560 nm and all use the echelle grating. We have not noticed any decrease in performance from the new wavelength range, but we caution the reader that we lack the necessary precision for these measurements. During this same period certain upgrades were made to the spectrograph collimator. All RV measurements over a time span of at least a year and typically longer, we classify a given star as single (strictly, non-RV variable) and finished, and move it to the lowest priority. If a given star has three RV measurements with a standard deviation $>2.0$ km s$^{-1}$ (four times our precision for narrow-lined stars; see Section 4.2), we classify the star as RV variable and give it the highest priority on observation on a schedule appropriate to its timescale of variability. This prioritization allows us to most efficiently derive orbital solutions for our detected binaries.

We place our shortest-period binaries at the highest priority for observations each night, followed by longer-period binaries to obtain 1–2 observations per run. Below the confirmed binaries we place, in the following order, “candidate binaries” (once observed stars with a RV measurement outside the cluster RV distribution or stars with a few measurements that span only 1.5–2.5 km s$^{-1}$, once observed and then twice observed non-RV-variable likely members, twice observed non-RV-variable likely non-members, unobserved stars, and finally, “finished” stars. Within each group, we prioritize by distance from the cluster center, giving those stars nearest to the center the highest priority. A typical pointing will contain $\sim$70 fibers placed on individual stars in our sample and $\sim$10 sky fibers.

For a given pointing, we obtain three consecutive exposures, each of 40 minutes. In poor transparency or with a particularly bright sky, we restrict the targets to $V < 15.0$ and shorten the integration time, generally to 20 minute exposures. We obtain thorium–argon (ThAr), or occasionally copper–argon (CuAr), emission-lamp comparison spectra (300 s integrations) before and after each set of science integrations for wavelength calibration and to check for wavelength shifts during the observing sequence. For each set of integrations, we also obtain one flat-field image (200 s) of a white spot on the dome illuminated by incandescent lights. Associating the flat-field images with the science integrations is particularly critical for calibrating throughput variations between the fibers in order to apply sky subtractions. In total, we have observed 106 distinct pointings in M35 over the roughly 11 years since our survey began.

2.3. Data Reduction

For a thorough description of our data-reduction process, see Geller et al. (2008). In short, we perform a standard bias and flat-field correction to the images using the overscan strip and the flat-field images, respectively. The flat-field spectra are used to trace each aperture in a given pointing and thereby extract the science spectra. Wavelength solutions derived from the emission-lamp spectra are applied, followed by sky subtraction using sky fibers from each pointing. The three sets of spectra (one set from each integration in a given configuration) are then combined via a median filter to remove cosmic-ray signals and improve S/N. These reduced spectra are cross-correlated with a high S/N solar spectrum, obtained using a dusk sky exposure taken on the WIYN 3.5 m with the same instrument setup as the given pointing. A Gaussian fit to the cross-correlation function (CCF) yields an RV and an FWHM (in km s$^{-1}$) for each stellar observation. The mean UT time is used to find and correct each RV measurement for Earth’s heliocentric velocity. Finally, we apply the unique fiber-to-fiber RV offsets derived by Geller et al. (2008) for the WIYN–Hydra data to these RVs. As in Geller et al. (2008), to ensure a sufficient quality of measurement, we incorporate into our database only those spectra with a CCF peak height higher than 0.4. Additionally, we examine the distribution of RVs for each individual star and visually

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9 http://www.astro.wisc.edu/~mab/research/bench_upgrade/
inspect any measurements that are outliers in the distribution. Occasionally we remove a measurement whose CCF, though having a peak height above 0.4, clearly provides a spurious measurement (e.g., inadequate sky subtraction).

2.4. Completeness of Spectroscopic Observations

We have at least one observation for 1144 of the 1344 stars in our stellar sample, for a completeness of 85% across our entire sample. Sixty percent of the stars in our stellar sample have sufficient observations for their RVs to be considered final (813/1344). For these stars, we either have \( \geq 3 \) RV measurements that show no variation, or, if we do see RV variability, we have found a binary orbital solution. (These 813 stars comprise the single member (SM), single non-member (SN), binary member (BM), and binary non-member (BN) classes; see Section 4.1.) Of those stars not finalized, 231 have only one or two observations, and another 100 stars are variable but do not yet have definitive orbital solutions.

In Figure 2, we show the completeness of our observations as functions of \( V \) magnitude (left) and projected radius (right). We plot the completeness in stars observed \( \geq 3 \) times with the dashed line, and stars observed \( \geq 1 \) time with the solid line.

The completeness toward fainter stars reflects the decreasing completeness with cluster radius. Our prioritization of stars by distance from the cluster center is evident by our decreasing completeness with cluster radius. The decreasing completeness toward fainter stars reflects the need for dark skies with minimal sky contamination in order to obtain sufficient S/N in our spectra to derive reliable RVs for faint stars. There are 37 stars with \( V < 15 \) in our stellar sample that do not have RV measurements, one of which is a proper-motion member. Fifteen were observed but did not yield reliable RVs, mostly due to rapid rotation. Twenty-two were not observed, 15 of which are farther than 20 arcmin in radius from the cluster center.

The difference in completeness between bright stars observed \( \geq 1 \) and \( \geq 3 \) times is also a result of an increasing population of rapidly rotating stars toward bluer (\( B - V \)) color. For many of these stars, we have multiple observations of which only a few, and sometimes one, exceed the cutoff value of CCF peak height \( > 0.4 \) and therefore are included in our database. For purposes of future research, we also include seven rapid rotators in Table 1 for which we have been unable to derive RVs from our spectra.

3. EFFECTS OF STELLAR ROTATION ON MEASUREMENT PRECISION

3.1. Observed Rotation

Because of its youth, M35 provides a sample of late-type stars with a range of rotational periods (Meibom et al. 2009); some of these stars have projected rotational velocities that exceed our spectral resolution. As such, the cluster presents an opportunity to explore empirically the dependence of our measurement precision on increasing \( v \sin i \), where \( i \) is the inclination angle of the stellar rotation axis to our line of sight.

The measured FWHM of the CCF for a given star is directly related to the \( v \sin i \) (Rhode et al. 2001). Thus in order to derive a \( v \sin i \) value, we first measure the FWHM of the CCF peak. To do so, we fit a Gaussian function to the peak, forcing the baseline of the Gaussian to start at the background level of the CCF. Specifically, we subtract from the CCF a polynomial fit to this background level, and then fit the Gaussian to the subsequent “continuum subtracted” CCF. We only use spectra from the 512.5 nm region to measure the FWHM, as the FWHM is dependent on the setup (i.e., the dispersion, etc.), and most of our observations were taken in the 512.5 nm region. We then use a similar technique as Rhode et al. (2001), to convert this FWHM to a \( v \sin i \). We create a series of artificially broadened templates by convolving our standard solar template with a series of theoretical rotation profiles of specific \( v \sin i \) values. We then cross-correlate this series of broadened templates with the original narrow-lined template and measure the FWHM of the CCF peak as described above. In Figure 3, we show the results of this analysis along with a polynomial fit to the data. We use this curve to derive \( v \sin i \) values for all observations of stars in M35 in the 512.5 nm region. We then take the mean \( v \sin i \) for each star, using only our highest-quality (CCF peak height \( > 0.4 \)) spectra, and provide these values in Table 1. We are unable to reliably measure \( v \sin i \) values below 10 km s\(^{-1}\), due to the spectral resolution; we therefore impose a floor to the \( v \sin i \) at this value.

The median FWHM value that we observe is 46.1 km s\(^{-1}\), which corresponds to \( v \sin i = 10.3 \) km s\(^{-1}\). Excluding stars rotating slower than 10 km s\(^{-1}\), we find a precision of 1.4 km s\(^{-1}\) for individual \( v \sin i \) values of \( \leq 25 \) km s\(^{-1}\), which increases to 1.6 km s\(^{-1}\) for \( v \sin i > 25 \) km s\(^{-1}\). These precision values were derived in the same manner as for our RV precision, with a fit to a \( \chi^2 \) function; see Section 3.2 and Geller et al. (2008). Where possible, we derive a mean \( v \sin i \) for a given star from multiple, generally \( \geq 3 \), observations within the 512.5 nm region. We have compared our \( v \sin i \) measurements to the...
rotation periods from Meibom et al. (2009) for stars observed in both studies, and find the \( v\sin i \) and rotation periods to be consistent.

In the left panel of Figure 4, we plot a histogram of the mean \( v\sin i \) measurements for M35 cluster members (see Section 4.1 for our membership criteria). In this and the other panel, we have excluded any binaries with periods known to be less than the circularization period in M35 of 10.2 days (Meibom & Mathieu 2005) as the rotation of the stars in these binaries has likely been affected by tidal processes. We have also removed any stars that appear to be in double-lined binaries, as the spectral lines in many of these observations are broadened due to the secondary spectrum at similar, though slightly offset, RV. In the right panel of Figure 4, we plot the mean \( v\sin i \) as a function of \((B-V)\) for M35 cluster members. We see a clear trend of increasing rotation toward bluer stars, as has also been observed in other young open clusters and the field (e.g., field, Hyades, Pleiades, Kraft 1967; Pleiades, Soderblom et al. 1993; Blanco 1, Mermilliod et al. 2008; IC 2391, Platais et al. 2007).

### 3.2. Radial-velocity Precision

We determine the RV measurement precision following Geller et al. (2008), where a \( \chi^2 \) distribution is fit to the distribution of the standard deviations of the first three RV measurements for each star in an ensemble of stars. Here, we do this operation on samples of stars with differing \( v\sin i \). Specifically, we consider stars with \( v\sin i \) of \( \leq 10 \) km s\(^{-1}\), 10–20 km s\(^{-1}\), and 20–80 km s\(^{-1}\). The bin sizes were chosen arbitrarily in order to provide sufficiently large samples. The first bin contains all narrow-lined stars for which we have imposed a floor to the \( v\sin i \) (see Section 3.1); these stars have line widths characteristic of the auto-correlation of our spectral resolution. The remaining bins contain stars with line widths increased by stellar rotation.

A detailed study of the RV measurement precision of our observation and data-reduction pipeline has been done by Geller et al. (2008) for late-type stars in the old open cluster NGC 188. For the narrow-lined stars in NGC 188, they find a single-measurement precision of 0.4 km s\(^{-1}\). This precision is also a function of the S/N of the spectrum, as shown in Geller et al. (2008) by the degrading precision with increasing \( V \) magnitude as well as decreasing CCF peak height. The largest S/N effect seen for narrow-lined stars in NGC 188 is to degrade the precision by 0.25 km s\(^{-1}\). The effect of rotation is larger than this amount. Here, we derive a relationship between the measurement precision and \( v\sin i \), and use this relationship in our analysis throughout this paper.

In Figure 5, we show the RV precision as a function of \( v\sin i \) in M35 for observations taken in the 512.5 nm region. The narrow-lined stars have a RV precision of 0.5 km s\(^{-1}\), similar to that found for the narrow-lined stars in NGC 188 observed with this same setup. As expected, the value of the measurement precision increases with increasing line width. For the most rapidly rotating stars \( (v\sin i > 50 \) km s\(^{-1}\)), the measurement precision degrades to \( \sim 1.0 \) km s\(^{-1}\). We fit a linear relationship to the points in Figure 5, shown as the dashed line:

\[
\sigma_i = 0.38 + 0.012(v\sin i) \text{ km s}^{-1},
\]

where \( \sigma_i \) is our precision. We use this equation with the mean measured \( v\sin i \) for a given star to calculate the single-measurement RV precision for that star. We adopt a floor to our precision at 0.5 km s\(^{-1}\), as found for our narrow-lined stars, and shown by the break in the dashed line in Figure 5.

We lack sufficient observations to perform this same analysis using observations in the 637.5 nm region or for observations taken after the spring of 2008 (see Section 2.2). Therefore, for the 129 stars that do not have any observations in the 512.5 nm region, we use the \( \sigma_i \) from the 637.5 nm region and do not fit a relationship to the data.
region (~11% of our observed stars), we visually inspect the spectra and CCFs. For narrow-lined stars, we set the precision to 0.5 km s$^{-1}$, and for rotating stars we set the precision to 1.0 km s$^{-1}$. We can then use this RV precision value for a given star to determine whether our observations for this star are constant or variable in velocity (see Section 4.2). We note that only 13 of these stars have sufficient observations for their RVs to be considered final, and only two are probable members.

4. RESULTS

The M35 database is shown in Table 1 (the full database is available in the online version of the journal). The first column in Table 1 contains the WOCS identification number (ID$_W$). These numbers are defined in the same manner as in Hole et al. (2009), with the cluster center set at $\alpha = 6^h 9^m 7.5^s$ and $\delta = +24^\circ 20' 28''$ (J2000). Next, we give the corresponding IDs from Melbom et al. (2009), McNamara & Sekiguchi (1986a), and Cudworth (1971) (ID$_M$, ID$_Mc$, and ID$_C$). The next few columns provide the right ascension (R.A.), declination (decl.), the $BV$ photometry, and the source number (S) for this photometry (see Section 2.1). Next, we show the number of RV measurements ($N$) and the mean and standard error of the RV measurements. For stars with only one RV measurement, we show the single-measurement RV precision instead of the standard error. Next, we provide this single-measurement RV precision ($\sigma_v$, derived using Equation (1)), the $e/i$ value (see Section 4.2), the calculated RV membership probability ($P_{RV}$, see Section 4.1), the proper-motion membership probability from McNamara & Sekiguchi (1986a, $P_{PM1}$) and Cudworth (1971, $P_{PM2}$), where available, and then, the classification of the object (see Section 4.3). For RV-variable stars with orbital solutions, we present the center-of-mass ($\gamma$) RV with the derived error in place of the mean RV and its standard error, and add the comment SB1 or SB2 for single- and double-lined binaries, respectively. Additionally, for binaries without orbital solutions that appear to be double lined, we add the comment of SB2. Finally, for purposes of future research we include seven rapid rotators for which we have been unable to derive RVs from our spectra, and label them with the comment RR.

4.1. Membership

The RV distribution of M35 is clearly distinguished from that of the field when we plot a histogram of the mean RVs for the observed stars in our stellar sample. In Figure 6, we show a histogram of the mean RVs for stars with $\geq 3$ RV measurements whose standard deviations are $<2.0$ km s$^{-1}$, as well as the $\gamma$-RVs for binary stars with orbital solutions, thus excluding from the fit any RV variables whose $\gamma$-RVs are unknown. The cluster shows a well-defined peak rising above the broad distribution of the field stars. We simultaneously fit one-dimensional Gaussian functions, $F_r(v)$ and $F_f(v)$, to represent the cluster and field RV distributions, respectively, and then use these fits to calculate RV membership probabilities for each individual star. We compute the membership probability $P_{RV}(v)$ with the usual formula

$$P_{RV}(v) = \frac{F_r(v)}{F_r(v) + F_f(v)}$$

(Vasilevsks et al. 1958). We plot these Gaussian fits in Figure 6 with the dashed lines, and show the fit parameters in Table 2.

| Parameter | Cluster | Field |
|-----------|---------|-------|
| Ampl. (Number) | 69.0 ± 2.0 | 2.4 ± 0.4 |
| RV (km s$^{-1}$) | $-8.17 ± 0.05$ | $13 ± 4$ |
| $\sigma$ (km s$^{-1}$) | $0.92 ± 0.08$ | $34 ± 4$ |

For a given single star, we use the mean RV to compute the RV membership probability. For a given binary star with an orbital solution, we compute the RV membership probability from the $\gamma$-RV. For RV-variable stars without orbital solutions, the $\gamma$-RVs are not known, and therefore we cannot calculate RV membership probabilities. For these stars, we provide a preliminary membership classification, described in Section 4.3.

In Figure 7, we show the distribution of RV membership probabilities, displaying a clean separation between the cluster members and field stars. In the following analysis, we use a probability cutoff of $P_{RV} \geq 50\%$ to define our cluster member sample. Using the 344 single cluster members and binary cluster members with orbital solutions, we find a mean cluster RV of $-8.16 ± 0.05$ km s$^{-1}$. From the area under the fit to the cluster and field distributions, we estimate a field contamination of 6% within our cluster member sample ($P_{RV} \geq 50\%$). Though this estimate is derived excluding the RV variables that do not have orbital solutions, the percent contamination should be valid for the cluster as a whole.

Our RV membership probabilities agree well with the proper-motion memberships of Cudworth (1971) and McNamara & Sekiguchi (1986a). We note that our stellar sample covers only the faintest portion of either proper-motion study. There are 24 Cudworth (1971) proper-motion members within our observed stellar sample, of which we find 14 (58%) to also have $\geq 50\%$ RV membership probabilities. Cudworth (1971) note that for $V > 13$ they begin to find significant errors in their photometry and expect many field stars to contaminate their proper-motion member sample; this can likely explain the 10 discrepant stars. There are 70 McNamara & Sekiguchi (1986a) proper-motion

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10 For double-lined binaries and stars with no observation in the 512.5 nm region, we do not derive a $v$ sin $i$ value. For stars with only one measurement in the 512.5 nm region, we convert the $1\sigma$ error on the FWHM (derived from the Gaussian fit to the CCF peak) to an error on the $v$ sin $i$ using the fit shown in Figure 3. As this relationship is not linear, we provide the mean of the derived upper and lower errors on $v$ sin $i$. 

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**Figure 6.** RV histogram for stars in the field of M35. We include the mean RVs for stars observed $\geq 3$ times with RV standard deviations $<2.0$ km s$^{-1}$ and the $\gamma$-RVs for binary stars with orbital solutions, excluding RV variables whose $\gamma$-RVs are unknown. The bin sizes are 0.5 km s$^{-1}$, equal to our RV precision for narrow-lined stars, as found in Section 3. The dashed lines show the simultaneous Gaussian fits to the cluster and field RV distributions.
members within our observed stellar sample, of which we find 64 (91%) to also have \( \geq 50\% \) RV membership probabilities. McNamara & Sekiguchi (1986a) expects up to 15 field stars contaminating their cluster member sample from \( 13 < V < 15 \), which can easily account for the 6 discrepant stars.

We also note that NGC 2158 is only \( \sim 28 \) arcmin away from the center of M35, at \( \alpha = 6^\mathrm{h}07^\mathrm{m}25^\mathrm{s} \) and \( \delta = +24^\circ05'48'' \) (J2000), and thus is within the spatial region that we have surveyed. Scott et al. (1995) find a mean RV for NGC 2158 of \( 28 \pm 4 \) km s\(^{-1}\). There are five stars within our sample that lie within the cluster radius of \( 2.5 \) arcmin (Carraro et al. 2002) from the center of NGC 2158 and have RVs within three times the standard error (12 km s\(^{-1}\)) of the mean RV; 125044, 39017, 111050, 57037, 54048. Two of these stars (125044 and 57037) have less than three observations; the remaining three have \( \geq 3 \) observations and appear to be non-RV variables.

### 4.2. Radial-velocity Variability

RV-variable stars are distinguishable by the larger standard deviations of their RV measurements. Here, we assume that such velocity variability is the result of a binary companion, or perhaps multiple companions. Specifically, we consider a star to be an RV variable if the ratio of the standard deviation of its RV measurements to the single-measurement RV precision\(^{11} \) \((e/i)\) for that star is greater than four (Geller et al. 2008). We provide the \( e/i \) value for each single-lined star in Table 1; we label double-lined systems as RV variables directly, and include the comment of SB2 in Table 1.

Monte Carlo analysis has shown that, for similar observations of solar-type stars in NGC 188, A. M. Geller & R. D. Mathieu (2010, in preparation) can detect the majority of binaries with periods less than \( 10^4 \) days and a negligible fraction of longer-period binaries. Though the slightly poorer precision for the M35 data will effect the specific completeness numbers, we can assume a similarly high completeness in detected binaries with periods less than \( 10^4 \) days and a corresponding drop in completeness for longer-period binaries. Some of the undetected systems are evident from their separation from the main sequence (see Figure 8).

We have currently identified 55 RV-variable members of M35, and have derived orbital solutions for 71% (39/55) of this sample. In following papers, we will provide the orbital solutions for these systems, including all derived parameters. We will then perform a detailed analysis of the distributions of these orbital parameters as well as the binary frequency of the cluster.

### 4.3. Membership Classification of Radial-velocity-variable Stars

We follow the same classification system as Geller et al. (2008) and Hole et al. (2009) in order to provide a qualitative guide to a given star’s membership and variability, in addition to the calculated RV memberships and \( e/i \) values. We provide these classifications for all observed stars, while the memberships and \( e/i \) values are only provided for a subset of appropriate stars.

For stars with \( e/i < 4 \), we classify those with \( P_{RV} \geq 50\% \) as SMs, and those with \( P_{RV} < 50\% \) as SNs. If a star has \( e/i \geq 4 \) and enough measurements from which we are able to derive an orbital solution, we use the \( \gamma \)-RV to compute a secure RV membership. For these binaries, we classify those with \( P_{RV} \geq 50\% \) as BMs and those with \( P_{RV} < 50\% \) as BNs. For RV variables without orbital solutions, we split our classifications into three categories. If the mean RV results in \( P_{RV} \geq 50\% \), we classify the system as a binary likely member (BLM). If the mean RV results in \( P_{RV} < 50\% \) but the range of measured RVs includes the cluster mean RV, we classify the system as a binary with unknown membership (BU). Finally, if the RV measurements for a given star all lie either at a lower or higher RV than the cluster distribution, we classify the system as a binary likely non-member (BLN), since it is unlikely that any orbital solution could place the binary within the cluster distribution. We classify stars with \( < 3 \) RV measurements as unknown (U), as these stars do not meet our minimum criterion for deriving RV memberships or \( e/i \) measurements. In the following analysis, we include the SM, BM, and BLM stars as cluster members. Including these stars, we find 360 total cluster members in our sample. We list the number of stars within each class in Table 3.

### 5. DISCUSSION

In the following section, we present a CMD for M35 cleaned of field star contamination (Section 5.1), compare the spatial distribution of the single and binary members (Section 5.2), and analyze the RV dispersion of the cluster (Section 5.3).

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\(^{11}\) We use the same nomenclature of “\( e/i \)” as in Geller et al. (2008), though in other sections, for clarity, we have labeled the precision as \( \sigma_i \), so as not to confuse the precision with an inclination angle.
and the dashed gray line shows the deviation from the isochrone of twice the solid gray line shows where binaries with mass ratios of 1.0 lie on the CMD, with diamonds. We show the 180 Myr Padova isochrone as the black line. The RV variables with orbital solutions with circles and without orbital solutions (Figure 8).

We derive the distance of each star from the main-sequence isochrone and identify binaries that lie far from the isochrone on the CMD. We define binaries as objects that have photometry from the WIYN 0.9 m (and are therefore shown in Figure 8), as these stars are likely long-period binaries that are outside of our detection limits, as the hard–soft boundary for solar-type stars in M35 is $\sim 10^5$–$10^6$ days, and we only detect binaries with $P \lesssim 10^4$ days (A. M. Geller & R. D. Mathieu 2010, in preparation).

5.2. Spatial Distribution and Mass Segregation

In Figure 9, we compare the cumulative projected radial distributions of the single and binary members of M35. We have attempted to reduce the contamination from undetected binaries within our single-star sample by only including stars with no detectable RV variation (SM) that are fainter and bluer than the dashed gray line in Figure 8. This conservative cut removes large-$q$ (i.e., high total mass) binaries that have periods longer than our detection limit. We have not applied any correction for the spatial bias found in our observations (Section 2.4), because this bias will be present in both the single- and binary-star samples and should therefore not affect this analysis. A Kolmogorov–Smirnov test shows no significant difference between these two populations with a value of 60%. We therefore conclude that the solar-type main-sequence binaries in M35 show no evidence for central concentration as compared to the single stars.

Mathieu (1983) finds a half-mass relaxation time for the cluster of 150 Myr, comparable to the cluster age. This study of the radial spatial distributions for proper-motion-selected member stars in the $8.0 < V < 14.5$ ($\sim 4.4$–$1.2 M_\odot$) range revealed mass segregation only among stars more massive than $2 M_\odot$. The degree of segregation lessens with decreasing mass, and is largely non-existent among solar-like stars. McNamara & Sekiguchi (1986b) found similar results in their proper-motion-selected sample, which covered stars down to $V = 14.5$ ($\sim 1.2 M_\odot$). We only include primary stars with masses of $1.6$–$0.8 M_\odot$, and therefore most of our binaries have total masses that are lower than the higher-mass stars that have been shown to be mass segregated. Mathieu (1983) found that M35 is fit well with a multi-mass King model. In such models, the reduction in mass segregation for lower-mass systems derives from more severe contamination within the cluster members sample (Section 4.1).
tidal truncation of higher-dispersion velocity distributions in a cluster potential dominated by the solar-like stars.

5.3. Cluster Radial-velocity Dispersion

To determine the true RV dispersion of the cluster, we follow the procedure of Geller et al. (2008). We first limit our sample to only include SM stars that have $v \sin i \leq 10$ km s$^{-1}$. We limit the $v \sin i$ value to ensure that we only use the highest precision RV measurements for this analysis. These narrow-lined stars have a precision $\sigma_i = 0.5$ km s$^{-1}$. We will discuss the effect of undetected binaries that likely remain within this sample in Section 5.3.1.

Using this sample of 67 SM stars, we first derive the observed dispersion $\sigma_{\text{obs}}$ by taking the standard deviation of the mean RVs for each star, and we find $\sigma_{\text{obs}} = 0.86 \pm 0.07$ km s$^{-1}$. This observed dispersion is a function of our measurement precision and is also inflated by undetected binaries. Therefore, in order to derive the true RV dispersion, we must first account for the precision on these RV measurements. We derive$^{12}$ the “combined RV dispersion” $\sigma_{\text{cb}}$ from

$$\sigma_{\text{cb}}^2 = \sigma_{\text{obs}}^2 - \frac{1}{n} \sum_{i=1}^{n} \xi_i^2. \quad (3)$$

Here, $n = 67$ is the number of stars used in this analysis, and $\xi_i$ is the mean error of the RV for the $i$th star defined as

$$\xi_i = \left( \frac{1}{m} \sum_{j=1}^{m} \frac{(RV_j - \text{mean RV})^2}{m(m-1)} \right)^{1/2} \quad (4)$$

where $RV_j$ is one of the $m$ number of RV measurements for a given star $i$, and $\text{mean RV}$ is the mean RV for that star. We note that the second term in Equation (3) is very nearly equal to $\sigma_i^2/3$, as we have 3 RVs for most of the stars in this sample, and these narrow-lined stars all have the same precision of $\sigma_i = 0.5$ km s$^{-1}$. Following this procedure, we derive a combined dispersion of $\sigma_{\text{cb}} = 0.81 \pm 0.08$ km s$^{-1}$. The error on this combined dispersion is almost entirely due to the statistical error on $\sigma_{\text{obs}}$.

We find no significant difference in the combined RV dispersion of the SM or BM stars. For the BM stars, we use the $\gamma$-RVs in place of the mean RVs, and substitute the measurement precision for the standard deviation portion in Equation (4). There is also no significant variation in the combined RV dispersion as a function of radius, although due to the small sample sizes our binned RV dispersion values have large uncertainties (of 0.1–0.15 km s$^{-1}$ for bins of 10 arcmin).

This combined RV dispersion is inflated by undetected binaries. In the following section, we quantify this effect and apply the correction to derive the true RV dispersion of M35, an improvement on the procedure of Geller et al. (2008).

5.3.1. Contribution from Undetected Binaries

The combined RV dispersion defined in Equation (3) is also described by

$$\sigma_{\text{cb}} = \sigma_c + \beta, \quad (5)$$

where $\sigma_c$ is the true RV dispersion of the cluster and $\beta$ represents the contribution from undetected binaries within our sample.

Therefore, in order to derive the true RV dispersion of the cluster we have performed a Monte Carlo analysis to determine this contribution from undetected binaries.

We first create a set of simulated binaries with orbital parameters distributed according to the Galactic field solar-type binaries studied by Duquennoy & Mayor (1991). Specifically, these binaries have a log-normal period distribution centered on $\log(P \text{ (days)}) = 4.8$ with $\sigma = 2.3$, and a Gaussian eccentricity distribution centered on $e = 0.3$. For binaries with periods below the circularization period of 10.2 days (Meibom & Mathieu 2005), we set the eccentricity to zero. We use only solar-mass primary stars, and a distribution in secondary mass between 0.08 and $1 M_\odot$ described by a Gaussian centered on $M_2 = 0.23 M_\odot$ with $\sigma = 0.42 M_\odot$ (Kroupa et al. 1990). Duquennoy & Mayor (1991) found this Gaussian to be the best fit to their solar-type field binaries, and this distribution is also consistent with that of Goldberg et al. (2003) for their field binaries with primary masses $>0.67 M_\odot$. The orbital inclinations and phases of the binaries are chosen randomly. We then generate three RVs for these simulated binaries distributed in time according to the actual distribution of our first three observations for stars in M35. The majority of the SM stars in our sample have only three observations. To these RVs, we also add a random error generated from a Gaussian centered on zero and with $\sigma = 0.5$ km s$^{-1}$, the RV precision for narrow-lined stars in M35. We also add a random velocity offset generated from a Gaussian centered on zero with a standard deviation equal to an adopted one-dimensional RV dispersion.

To this sample, we add a number of simulated single stars to produce a desired binary frequency. We generate three RVs for each single star from a Gaussian described by our precision. To the mean RV for every single star we also add a random offset described by the assumed RV dispersion in the same manner as for the simulated binaries. We then keep only those simulated binaries (and single stars) whose first three RVs result in an $e/i < 4$, and whose mean RVs are within three standard deviations of the mean RV from a Gaussian fit to the simulated RV distribution. This cutoff in standard deviation reflects our membership criterion of $P_{\text{RV}} \geq 50\%$ for the M35 observations. These binaries would be undetected within the SM sample.

We then follow the equations given above to derive $\beta$ for a range of binary frequencies and velocity dispersions, $\sigma_c$. In Figure 10, we plot the true cluster RV dispersion ($\sigma_c$) as a function of the combined RV dispersion ($\sigma_{\text{cb}}$) for a range of total binary frequencies, where each line corresponds to a different binary frequency between 0% (far left) and 100% (far right) in steps of 10%. We can then use the results shown in Figure 10 to derive the true RV dispersion for M35. Furthermore, the results shown in this figure are also applicable to RV dispersion analyses for other star clusters, provided that the binary population is consistent with the Duquennoy & Mayor (1991) field binaries.

5.3.2. True Radial-velocity Dispersion

To date, we have detected 55 binaries in M35 out of 360 cluster members. If we assume a similar completeness as in A. M. Geller & R. D. Mathieu (2010, in preparation), for NGC 188, then we can assume that we have detected 63% of the binaries with periods less than $10^4$ days (and a negligible fraction of binaries with longer periods). This correction results in a binary frequency of $24\% \pm 3\%$ for $P < 10^4$ days. This binary frequency is consistent with that of solar-type stars in the Galactic field (Duquennoy & Mayor 1991) out to the same period limit. If we assume the M35 binaries follow a
Duquennoy & Mayor (1991) period distribution, then our binary frequency for $P < 10^4$ days implies a total binary frequency of 66% ± 8%, with the inclusion of wider binaries currently beyond our detection limits. We then take this value for the total binary frequency and correct our combined RV dispersion for undetected binaries.

In the filled gray areas in Figure 10, we show the regions defined by our M35 combined RV dispersion and the total binary frequency. At the intersection, we plot the derived true RV dispersion in M35 of $\sigma_c = 0.65 \pm 0.10$ km s$^{-1}$. Using a flat distribution in secondary mass (and mass ratio), as has been suggested by some studies (e.g., Mazeh et al. 1992, 2003), has a negligible effect on the derived true RV dispersion. This true RV dispersion is consistent with the projected velocity dispersion of 1.0 ± 0.15 km s$^{-1}$, derived by Leonard & Merritt (1989) using the proper-motion data from McNamara & Sekiguchi (1986a).

6. SUMMARY

This is the first paper in a series studying the dynamical state of the young ($\sim 150$ Myr) open cluster M35 (NGC 2168). In this first paper, we present our RV observations and provide initial results from this survey. Our stellar sample extends to 30 arcmin in radius from the cluster center (7 pc in projection at a distance of 805 pc or $\sim$4 core radii), and we have selected a region from a $V, (B-V)$ CMD (Figure 1) which covers a mass range of 1.6–0.8 $M_\odot$. We have used the WIYN 3.5 m telescope with the Hydra MOS to obtain 5201 spectra of 1144 stars within this stellar sample. From these spectra, we derive RV measurements with a precision of 0.5 km s$^{-1}$ for normalized lines. The vast majority of the observed stars have multiple measurements, allowing determination of cluster membership and identification of spectroscopic binary stars. We detect 360 cluster members, 55 of which show significant variability in their RV measurements. Binary orbital solutions have been obtained for 39 of these RV variables, which we will present in detail in the next paper in this series. Observations of the rest of the RV variables and the remainder of our stellar sample are ongoing. Table 1 provides the first RV membership database for M35 and extends $\sim$1.5 mag deeper than any previous membership catalog.

Using the RV cluster members, we study the spatial distribution and velocity dispersion of the single and binary stars. We find their spatial distributions to be indistinguishable. This lack of central concentration for the binaries is consistent with earlier observational studies of stars in M35 as well as with a fully relaxed dynamical model for the cluster (Mathieu 1983; McNamara & Sekiguchi 1986b). In these studies, mass segregation is seen in higher-mass stars, but diminishes to being undetectable for stars in our observed mass range. After correcting for measurement precision, but not for binaries, we place an upper limit on the RV dispersion of the cluster of 0.81 ± 0.08 km s$^{-1}$. When we also correct for undetected binaries, we derive a true RV dispersion of 0.65 ± 0.10 km s$^{-1}$.

The WOCS group will continue our survey of M35 in order to derive RV memberships for all stars in our stellar sample and obtain orbital solutions for all binaries with periods less than a few thousand days, as well as some with longer periods. In future papers, we will study the binary population of M35 in detail, providing all orbital solutions and analyzing the binary frequency and distributions of orbital parameters. These data will form essential constraints on the hitherto poorly known initial binary populations used in sophisticated $N$-body models of open clusters.

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