WIYN OPEN CLUSTER STUDY. LIX.: RADIAL-VELOCITY MEMBERSHIP OF THE EVOLVED POPULATION OF THE OLD OPEN CLUSTER NGC6791

Ref: arXiv:1408.3117

ACCEPTED TO THE ASTRONOMICAL JOURNAL JULY 28, 2014
Preprint typeset using LaTeX style emulateapj v. 08/22/09

WIYN OPEN CLUSTER STUDY. LIX. RADIAL-VELOCITY MEMBERSHIP OF THE EVOLVED POPULATION OF THE OLD OPEN CLUSTER NGC 6791

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Accepted to The Astronomical Journal July 28, 2014

ABSTRACT

The open cluster NGC 6791 has been the focus of much recent study due to its intriguing combination of old age and high metallicity (∼8 Gyr, [Fe/H]=+0.30), as well as its location within the *Kepler* field. As part of the WIYN Open Cluster Study, we present precise ($\sigma = 0.38$ km s^{-1}) radial velocities for proper-motion candidate members of NGC 6791 from Platais et al. Our survey, extending down to $g' \sim 16.8$, is comprised of the evolved cluster population, including blue stragglers, giants, and horizontal branch stars. Of the 280 proper-motion-selected stars above our magnitude limit, 93% have at least one radial-velocity measurement and 79% have three measurements over the course of at least 200 days, sufficient for secure radial-velocity-determined membership of non-velocity-variable stars. The Platais et al. proper-motion catalog includes twelve anomalous horizontal branch candidates blueward of the red clump, of which we find only four to be cluster members. Three fall slightly blueward of the red clump and the fourth is consistent with being a blue straggler. The cleaned color-magnitude diagram shows a richly populated red giant branch and a blue straggler population. Half of the blue stragglers are in binaries. From our radial-velocity measurement distribution we find the cluster's radial-velocity dispersion to be $\sigma_c = 0.62 \pm 0.10$ km s^{-1}. This corresponds to a dynamical mass of $\sim 4600\ M_{\odot}$.

NGC 6791

(RA,DEC) = 19 20 53, +37 46.3
(Gl, Gb) = 69.96, +10.9
Dist = 4 kpc

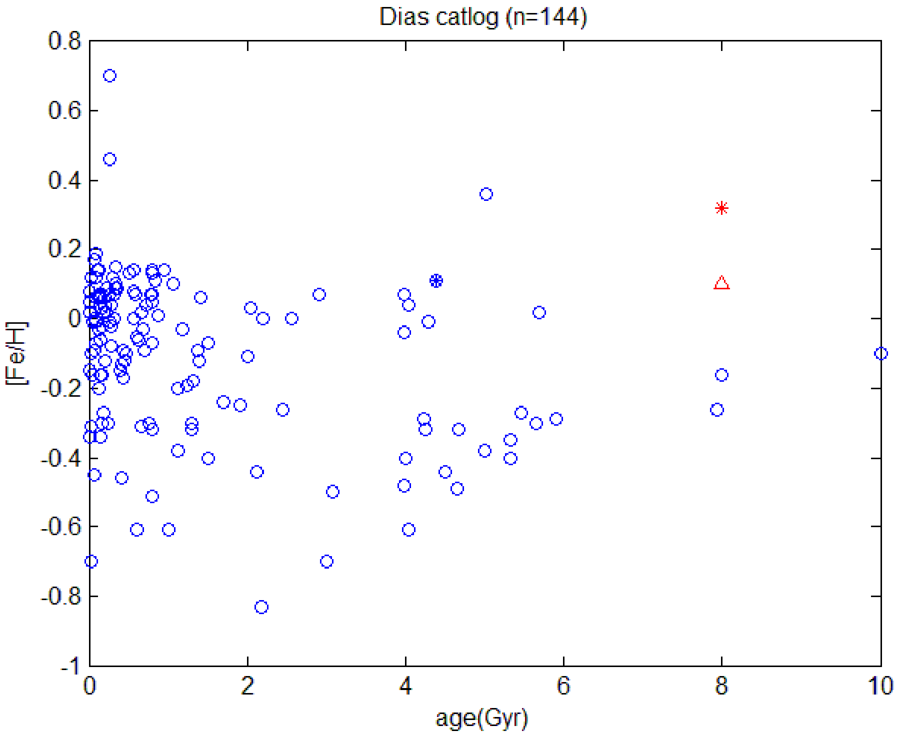
- Massive ~ 5000$M_{\odot}$
- Old ~ 8 Gyr
- Metal rich ~ 0.32 dex

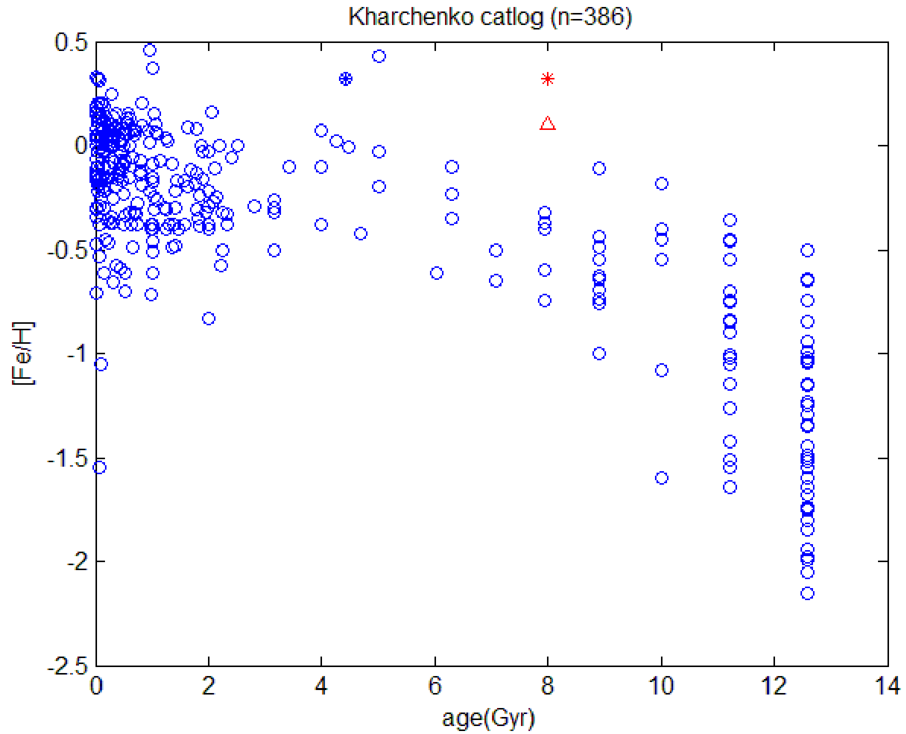
Evidence for extended star formation
Δt~ 1Gyr (Twarog et al.2011)

An SDSS view (27’*28’)

NGC 6791 in the OC catlog

Unique – both old & metal rich





Proper motion membership (Platais et al. 2011, P11):

- PM catlog 58901 objects down to g~24, radius~34';
- For g < 22, prb>19% ➔ 4800 probable members

This work: from P11

- g < 16.8, prb>19% + few more lower prb

Observations:

- Multi-Object Spectrograph (MOS), ~70 spectra over 1deg FOV R~20000;
- 1189 RV measurements for 260 stars IRAF data reduction

WIYN 3.5m telescope
Kitt peak

RV precision

- The best fit precision σ_i =0.38 km/s,
- σ_{max} =0.7 km/s, cutoff to limit binary contamination
- σ_{obs} > 4 σ_i as velocity variables

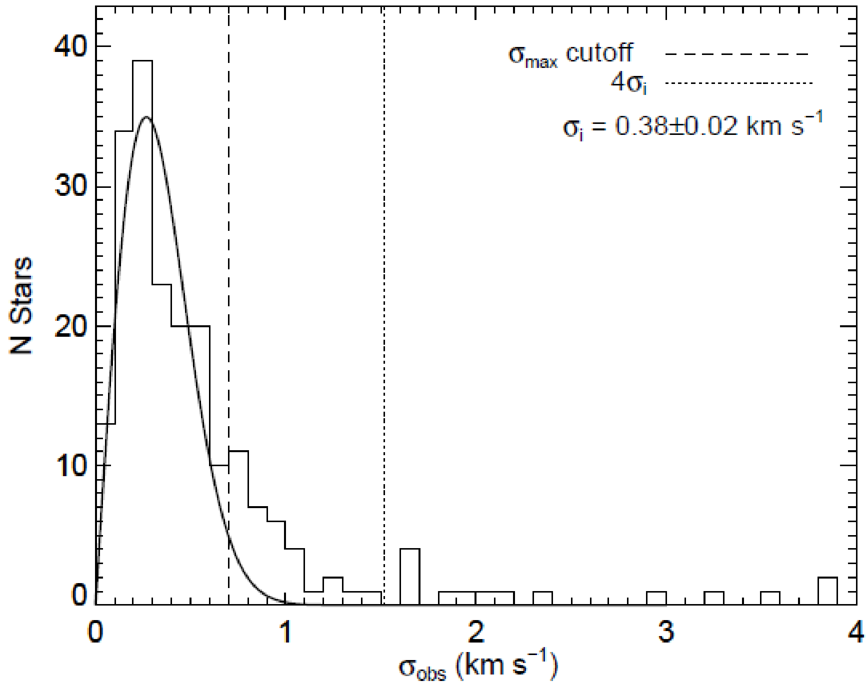


Figure 2. Distribution of the standard deviation of the first 3 RV measurements for each star. The solid curve displays the best fit of the χ^2 model within the $\sigma_{\max}$ cutoff represented by the dashed vertical line. A best-fit precision of $\sigma_i = 0.38 \pm 0.02$ km s^{-1} is found. The vertical dotted line marks $4\sigma_i$, the minimum standard deviation required for a velocity-variable designation.

RV results:

Table 1
Radial Velocity Summary Table

ID_W	R.A.	Dec.	g'	g'-r'	N_{obs}	$\overline{RV}$	P_μ	P_{RV} [a]	e/i	Class	Comment
1002	19:20:55.11	37:47:16.3	14.63	1.41	5	-47.51	99	96	0.31	SM	
1003	19:20:50.04	37:47:28.2	13.50	0.95	1	-49.49	10	...	...	U	
1004	19:20:58.63	37:47:40.5	11.99	0.88	3	-13.21	10	0	0.70	SN	
2003	19:20:47.66	37:47:32.3	15.33	1.23	3	-54.20	99	(0)	53.30	BU	SB1
3006	19:20:49.72	37:43:42.7	14.83	1.50	4	-46.47	99	94	1.30	SM	C_2 Band
4003	19:20:59.95	37:46:03.3	15.15	0.28	13	-44.76	99	54	1.62	SM	BSS
6006	19:20:49.65	37:44:07.8	15.18	1.10	3	-49.03	10	(89)	4.26	BLM	SB1
7021	19:20:33.03	37:55:55.9	14.21	1.10	14	-75.11	41	(0)	11.00	BLN	SB1
7045	19:21:22.34	38:07:57.1	14.04	0.39	10	-1.88	37	(0)	3.22	SN	RR (113.1 km s^{-1})
43033	19:22:15.20	37:48:47.2	15.82	0.55	6	-41.70	6	(0)	79.28	BU	SB2

Note. — This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and contents. Photometry, coordinates, and proper-motion membership probabilities come from I. Platais et al (2014, in preparation).

[a] RV membership probabilities in parenthesis indicate the probability of the mean RV for velocity variables ($P_{\overline{RV}}$) and remains uncertain until a binary orbital solution is found.

Class.

SB1/SB2: single/double lines spectro-binary; C_2 band:strong C_2 absorption;

BSS: blue straggler; RR: rapidly rotating stars

RV membership

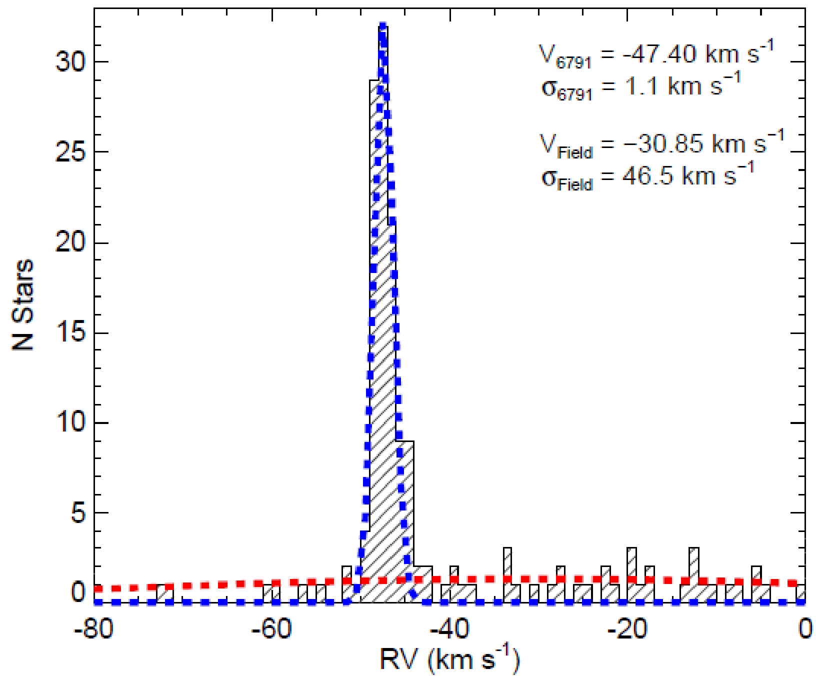


Figure 4. Radial-velocity histogram of single, non-rapidly rotating stars. Gaussian fits to the field and cluster RV distributions are over-plotted in red and blue respectively. Top right provides the radial-velocity mean and standard deviation for each of these fits.

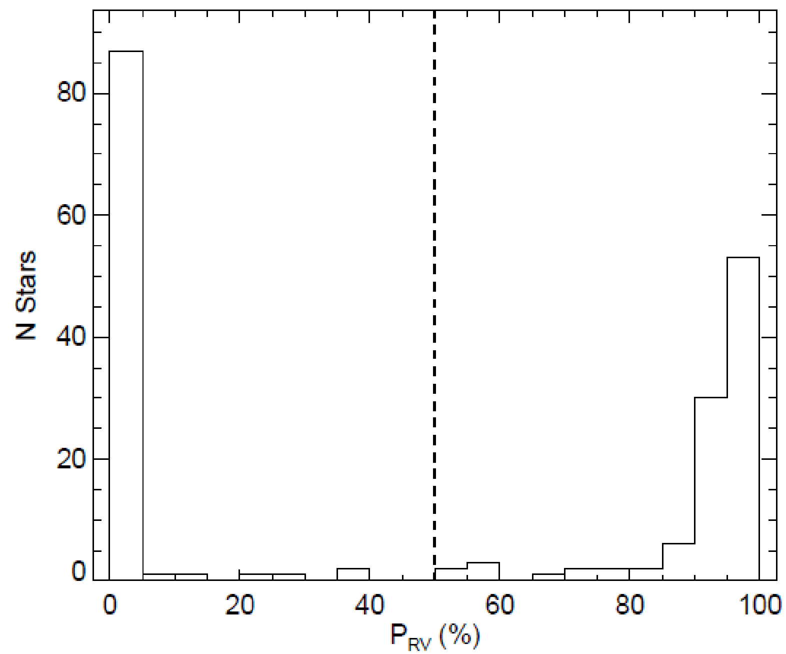


Figure 5. RV membership probability histogram for single stars. We set an RV membership cutoff at 50%, shown by the vertical dashed line.

Two-Gaussians fit

V_{6791}=-47.4 km/s, σ = 1.1 km/s

V_{field} =-30.8 km/s, σ = 46.5 km/s

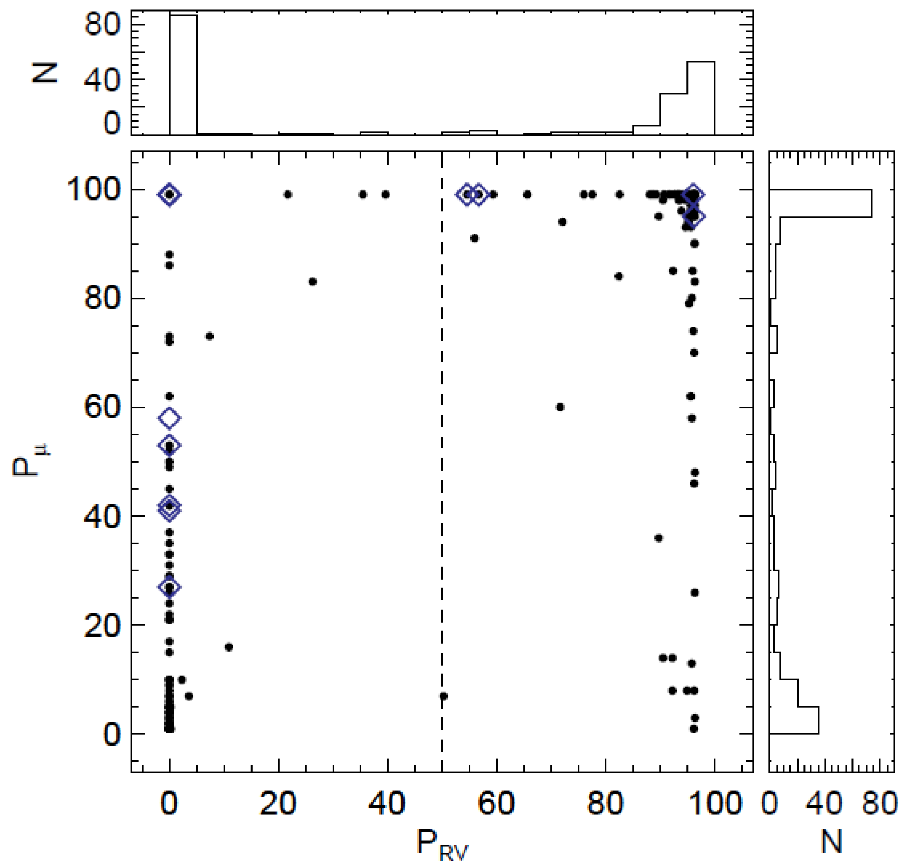


Figure 6. A comparison of the P11 P_μ values (y-axis) with our P_{RV} values (x-axis) for single stars. The dashed vertical line represents the radial-velocity membership criterion (50%). The blue-HB candidates from P11 are highlighted in blue diamonds. Blue diamonds without a central point are velocity variable. Their radial-velocity membership position reflects the membership probability of their mean radial velocity. Marginal distributions along each axis are presented in the top and right panels.

Cleaned CMDs with membership information

- Find 91 single members and 6 binary likely members in RGB & RC
- Of the 12 blue-HB candidates by P11, here only 4 to be members; three fall just blue of RC→evolved BSSs, another one to be a BSS;

➔A blue-HB population NOT supported by RV membership result.

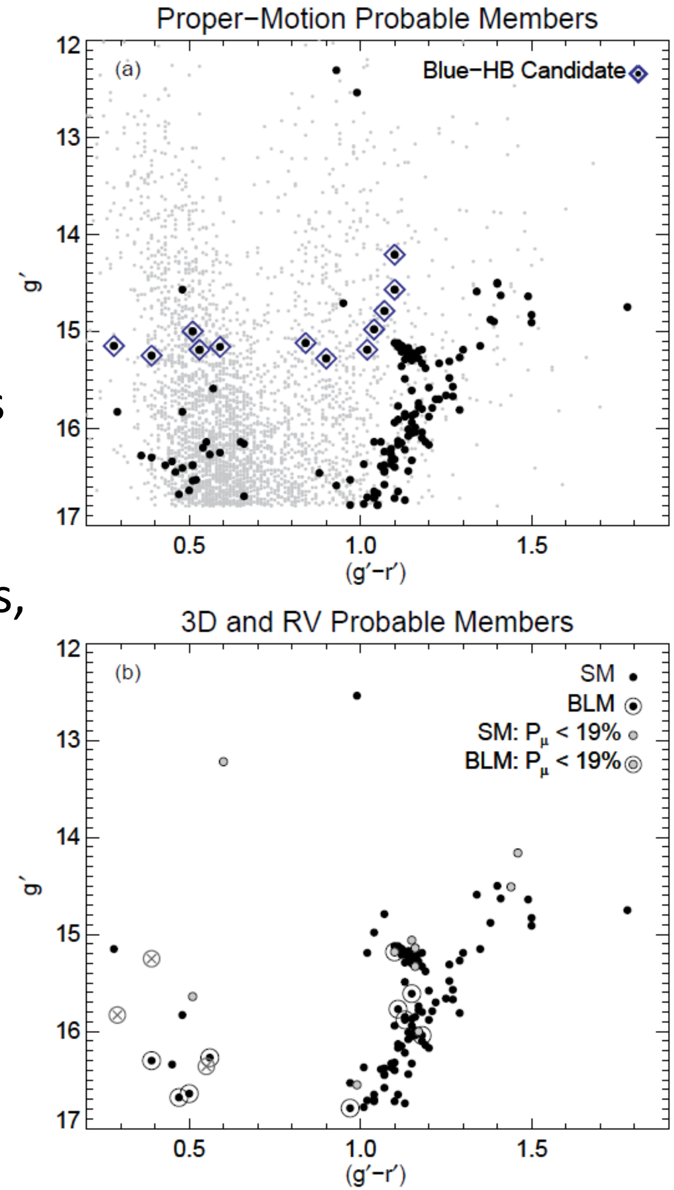


Figure 7. (a) Upper CMD of proper-motion probable members ($P_\mu \geq 19\%$) from P11 with blue-HB candidates highlighted in blue diamonds. Small light-gray points are stars with $P_\mu < 19\%$. (b) CMD including radial-velocity membership determinations. Single members (SMs) are shown as black points, circled points indicate binary likely members (BLMs). Gray points are SMs and BLMs with $1\% \leq P_\mu < 19\%$. Gray "⊗" symbols mark candidate binary members currently classified as binary unknowns (BUs) or binary likely non-members (BLNs), discussed in Section 6.1.

Research in Astron. Astrophys. **2010 Vol. 10 No. 8**, 761–776
http://www.raa-journal.org *http://www.iop.org/journals/raa*

*R*esearch in
*A*stronomy and
*A*strophysics

Our previous work

Kinematic and chemical properties of five open clusters based on SDSS DR7 *

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Received 2010 March 31; accepted 2010 April 28

Abstract We present metallicities and radial velocities for five old open clusters (NGC 6791, NGC 2420, NGC 2682, NGC 2158, and NGC 7789) using data from the seventh public data release of the Sloan Digital Sky Survey (SDSS), which includes the directed stellar program SEGUE: Sloan Extension For Galactic Understanding and Exploration. The radial velocities are used to calculate cluster membership probabilities for stars in each cluster region. NGC 6791, NGC 2420, NGC 2682, NGC 2158 and NGC 7789 are found to have mean metallicities [Fe/H]= $+0.08 \pm 0.09$, -0.38 ± 0.11, -0.08 ± 0.05, -0.41 ± 0.13 and -0.19 ± 0.13 dex (s.d.), respectively. The mean radial velocities for NGC 6791, NGC 2420, NGC 2682, NGC 2158 and NGC 7789 are $V_r = -45.9 \pm 0.2$, $+76.1 \pm 0.2$, $+35.0 \pm 0.2$, $+26.9 \pm 0.2$ and -48.2 ± 0.2 km s^{-1}(s.e.m.), respectively. We have compared our results with the values from literatures, and found that our metallicity of NGC 6791 is significantly underestimated (by about 0.3 dex) and our radial velocities of the open clusters agree well with the values derived using high-resolution spectroscopy.

RV membership estimation

3 RADIAL VELOCITIES AND METALLICITIES

3.1 Determination of Cluster Membership

The estimation of the membership probability involves the radial velocity (RV) distributions for both field and cluster stars. We assume that the RVs of cluster members follow a Gaussian distribution and field stars follow another Gaussian distribution. Then the distribution function for field stars, Φ_{fi}, and for cluster stars, Φ_{ci}, can be written as

$$\Phi_{fi} = \frac{1-n_c}{2\pi(\sigma_{f0}^2+\epsilon_i^2)}\alpha_i, \quad \Phi_{ci} = \frac{n_c}{2\pi(\sigma_{c0}^2+\epsilon_i^2)}\beta_i, \tag{1}$$

$$\alpha_i = \exp\left\{-\frac{1}{2}\left[\frac{(v_i-v_f)^2}{\sigma_{f0}^2+\epsilon_i^2}\right]\right\}, \tag{2}$$

$$\beta_i = \exp\left\{-\frac{1}{2}\left[\frac{(v_i-v_c)^2}{\sigma_{c0}^2+\epsilon_i^2}\right]\right\}, \tag{3}$$

where n_c is the normalized number of member stars, v_i is the radial velocity of the i-th star and ε_i the estimated observational error. (v_f, v_c) are the RV distribution centers of field stars and cluster members respectively, and $(\sigma_{f0}, \sigma_{c0})$ the intrinsic RV dispersions of field stars and cluster members.

These five parameters, n_c, (v_f, v_c) and $(\sigma_{f0}, \sigma_{c0})$, were estimated by a maximum likelihood method. In order to search for the maximum of the likelihood function, a bipartition algorithm was adopted (Wang 1997). We list distribution parameters of the five open clusters in Table 2.

After the distribution parameters are determined, the membership probability of the i-th star can be calculated as:

$$P_i = \frac{\Phi_{ci}}{\Phi_i} = \frac{\Phi_{ci}}{\Phi_{ci}+\Phi_{fi}}. \tag{4}$$

Table 2 Distribution Parameters of the Five Open Clusters

Parameter	NGC 6791	NGC 2420	NGC 2682	NGC 2158	NGC 7789
n_c	0.41	0.36	0.46	0.48	0.24
v_c	–45.9	75.9	35.1	26.6	–48.0
σ_c	2.3	2.1	1.5	2.6	3.4
v_f	–25.6	36.7	48.2	12.0	–42.2
σ_f	34.1	35.7	33.1	22.4	23.9

Properties of NGC 6791 member stars

Table 3 SSPP Parameters and Membership Probabilities of Selected Stars for NGC 6791

Plate	MJD	Fid	RA (°)	Dec (°)	RV (km s^{-1})	RV err (km s^{-1})	[Fe/H] (dex)	[Fe/H] err (dex)	S/N	*P*
2821	54393	179	290.23318	37.69495	−46.1	1.0	0.03	0.05	67.7	0.92
2821	54393	493	290.73611	38.19503	−46.7	0.9	−0.07	0.02	61.1	0.92
2800	54326	496	290.36243	37.83635	−45.1	0.8	0.18	0.08	47.0	0.92
2800	54326	482	290.57947	37.92975	−46.8	0.9	−0.11	0.01	54.5	0.92
2800	54326	180	290.22034	37.75919	−46.8	0.5	0.20	0.08	62.7	0.92
2821	54393	141	290.29285	37.73219	−46.5	1.0	0.05	0.06	47.8	0.92
2800	54326	154	290.25604	37.80142	−46.2	1.3	0.13	0.04	55.2	0.92
2800	54326	190	290.17673	37.76421	−46.3	1.1	0.17	0.05	51.1	0.92
2800	54326	161	290.26886	37.72120	−46.2	1.3	−0.04	0.12	30.3	0.92
2800	54326	185	290.16345	37.74368	−46.7	0.7	0.10	0.06	61.2	0.92
2800	54326	471	290.21030	37.83430	−46.1	1.3	0.23	0.13	36.3	0.92
2821	54393	173	290.23404	37.72550	−46.4	1.2	0.08	0.08	39.8	0.92
2821	54393	174	290.27438	37.76822	−46.0	1.2	0.03	0.06	37.5	0.92
2800	54326	189	290.16876	37.78517	−45.9	1.1	0.12	0.13	38.7	0.92
2800	54326	170	290.21915	37.74116	−45.8	1.3	0.14	0.03	64.4	0.92
2821	54393	472	290.26776	37.82575	−45.6	1.0	0.14	0.09	42.6	0.92
2821	54393	194	290.18384	37.77736	−45.3	1.0	0.06	0.06	49.0	0.92
2821	54393	436	290.12585	37.81327	−45.2	1.1	0.05	0.06	43.5	0.92
2800	54326	424	290.13763	37.82931	−46.0	1.8	0.19	0.04	24.6	0.91
2821	54393	177	290.25525	37.78111	−44.6	1.1	0.05	0.04	40.7	0.91
...	...	...	...	...	...	...	...	...	...	...

Membership histogram

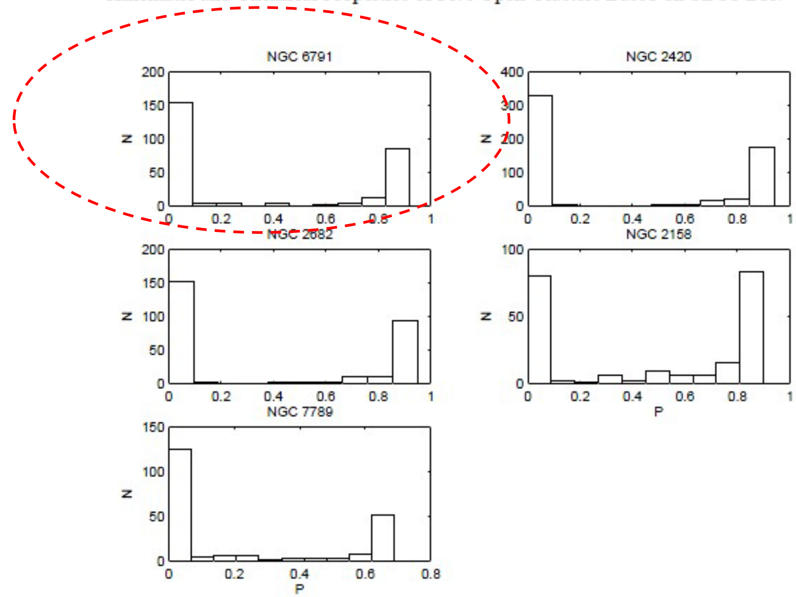

Fig. 1 Histogram of membership probabilities for stars in the five open cluster regions.

RV distributions for member/field stars

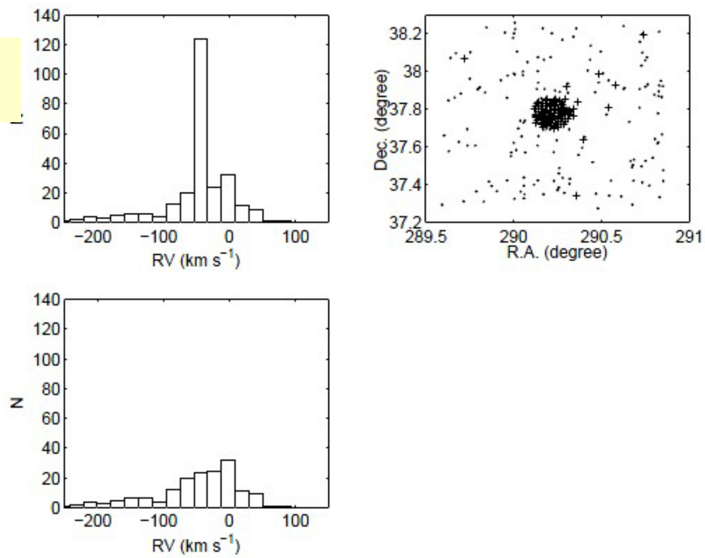

Fig. 2 (*Top left*) Distributions of RVs for all stars in the region of NGC 6791; (*Top right*) The black crosses indicate stars with membership probabilities $P \geq 0.7$ in the region of NGC 6791, and the black dots indicate stars with membership probabilities $P < 0.7$; (*Bottom left*) Distributions of RVs for field stars ($P < 0.7$) in the region of NGC 6791.

[Fe/H] for member stars:

- Inconsistency with high-R results

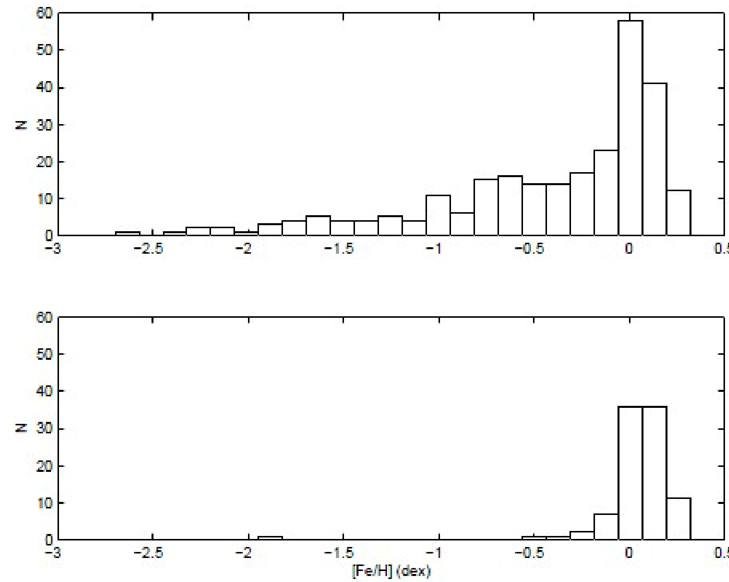

Fig. 3 (*Top*) Distributions of [Fe/H] for all stars in the region of NGC 6791; (*Bottom*) Distributions of [Fe/H] for cluster members ($P \geq 0.7$).

Table 4 Comparison of the SSPP-derived Metallicities with Metallicities Derived from Higher Resolution Spectra of the Same Stars in NGC 6791

ID	R.A. (J2000.0)	Dec (J2000.0)	$[Fe/H]^a$	$[Fe/H]^b$	P
10898	19 21 01.13	+37 42 13.80	0.38 ± 0.08	0.15 ± 0.05	0.90
11814	19 21 04.27	+37 47 18.90	0.34 ± 0.08	0.07 ± 0.06	0.91
8082	19 20 52.89	+37 45 33.40	0.38 ± 0.05	0.20 ± 0.08	0.92
2014	19 21 01.10	+37 46 39.60	0.40	0.08 ± 0.06	0.81

Notes: $[Fe/H]^a$ are the metallicity values based on high-resolution spectra; stars 10898, 11814 and 8082 are from Carraro et al. (2006) and star 2014 is from Gratton et al. (2006); $[Fe/H]^b$ values are calculated by SSPP; P is the membership probability in this work.

We concluded:

“In this work, comparing our metallicity value(0.08) for NGC 6791 with those from high-resolution spectroscopy implies that the SSPP of DR7 has still underestimated metallicity for stars with solar or super-solar metallicities.”

Revisited with SDSS-DR8

第 52 卷 第 4 期
2011 年 7 月

天 文 学 报
ACTA ASTRONOMICA SINICA

Vol.52 No.4
Jul., 2011

基于 SDSS-DR8 及 2MASS 数据的疏散星团 NGC 6791 的基本性质研究*

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摘要 利用斯隆数字巡天 (SDSS) 第 8 次释放数据 (DR8) 的恒星光谱数据及 2MASS (Two Micro All Sky Survey) 近红外点源测光数据研究著名的疏散星团 NGC 6791, 得到该星团的视向速度与金属丰度分别为 $V_r = -46.4 \pm 0.2$ km·s^{-1} 和 [Fe/H]= 0.32 ± 0.11 dex. 利用星团中红团簇巨星作为理想 “标准烛光”, 结合 2MASS 近红外点源测光数据计算了该星团的绝对距离模数为 $(m\text{-}M)_0 = 13.02 \pm 0.08$ mag 或 4.02 ± 0.15 kpc. 与其他研究者给出的结果进行了比较, 金属丰度、视向速度及绝对距离模数都符合得比较好. 主要结论有 3 点: (1) NGC 6791 是个极度富金属的星团; (2) 在 SDSS 的光谱分辨能力以内, 分离出的 87 颗团星之间不存在明显的金属丰度差异; (3) 得到的距离模数对年龄、金属丰度及尘埃消光不敏感, 是一种可靠的间接测量.

Conclusions:

- Metal rich (confirmed)
- No evident dispersion of [Fe/H] (87 members)

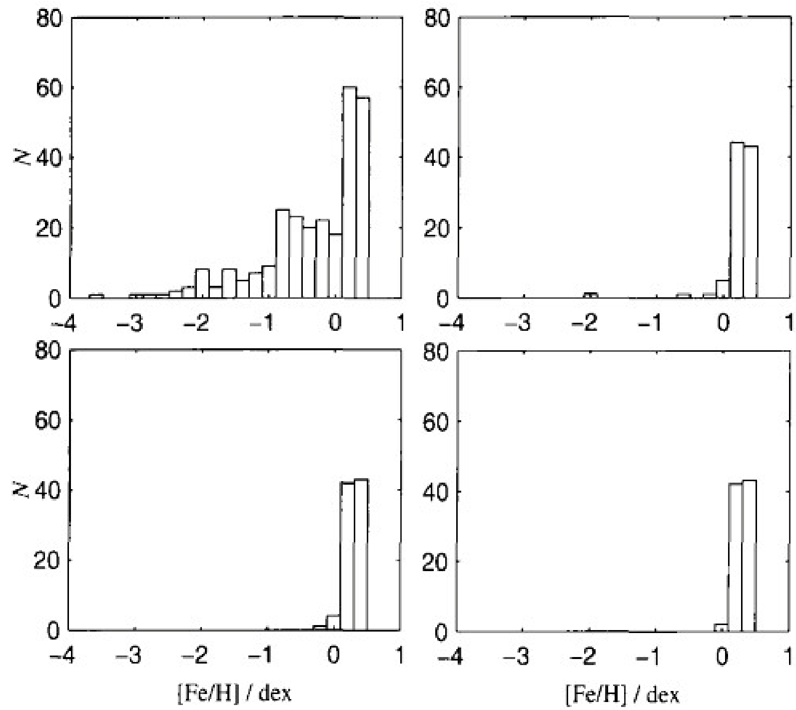

图 4　左上：274 颗样本恒星的 [Fe/H] 分布直方图；右上：95 颗 $P > 0.7$ 的样本恒星 [Fe/H] 分布直方图；左下：剔除潮汐半径以外样本后，90 颗 $P > 0.7$ 的恒星的 [Fe/H] 分布直方图；右下：剔除大于平均值 3 倍中误差的样本后，87 颗成员星的 [Fe/H] 分布直方图

Fig. 4　Top left: Distribution of [Fe/H] for 274 stars; Top right: Distribution of [Fe/H] for 95 stars with $P > 0.7$; Bottom left: Distribution of [Fe/H] for 90 stars lying inside the tidal radius and with $P > 0.7$; Bottom right: Distribution of [Fe/H] for 87 stars lying inside the tidal radius and with $P > 0.7$ after 3σ clip

Ideas for LAMOST OC_data analysis

- ~300 OCs (r<0.8') with observed objects >100
- LAMOST RV precision ~10km/s

➔ possible to separate when mean (OC RV – field RV) >10km/s