The Astrophysical Journal, 834:114 (5pp), 2017 January 10 doi:10.3847/1538-4357/834/2/114

BRIGHT TIMES FOR AN ANCIENT STAR

K. Fuhrmann[1,2] and R. Chini[1,3]
[1] Astronomisches Institut, Ruhr-Universität Bochum, Universitätsstraße 150, D-44801 Bochum, Germany; fuhrmann@astro.rub.de
[2] Isaac Newton Group of Telescopes, Apartado 321, E-38700 Santa Cruz de La Palma, Spain
[3] Instituto de Astronomía, Universidad Católica del Norte, Avenida Angamos 0610, Casilla 1280, Antofagasta, Chile
Received 2016 November 1; revised 2016 November 23; accepted 2016 November 23; published 2017 January 9

ABSTRACT

Field stars of Population II are among the oldest sources in the Galaxy. Most of their solar-type dwarfs are non-single and, given their extreme age, a significant fraction is accompanied by stellar remnants. Here we report the discovery of the bright F7V star 49 Lib as a massive and very metal-rich Population II field blue straggler, along with evidence for a white dwarf as its dark and unseen companion. 49 Lib is known as a relatively fast-rotating, single-lined spectroscopic binary in a 3 year orbit and with an apparent age of about $\tau \simeq 2.3$ Gyr. Its chemistry and kinematics, however, both consistently imply that 49 Lib must be an ancient Population II star at $\tau \simeq 12$ Gyr. With reference to the inclination from the astrometric orbit, leading to a $M_{\rm WD} = 0.50^{+0.03}_{-0.04}\,M_\odot$ low-mass white dwarf, and in view of the $M_{\rm BS} = 1.55^{+0.07}_{-0.13}\,M_\odot$ massive, evolved F-type blue straggler star, we demonstrate that 49 Lib must have been the subject of a mostly conservative mass transfer with a near-equal-mass $M \simeq 1.06 + 1.00\,M_\odot$ G-type binary at birth. For its future evolution, we point to the possibility as a progenitor system toward a type Ia supernova. Most importantly, however, we note that the remarkable metal enrichment of 49 Lib at [Mg/H] = +0.23 and [Fe/H] = −0.11 has principally very relevant implications for the early epoch when the Milky Way came into being.

Key words: blue stragglers – stars: fundamental parameters – stars: individual (49 Lib) – stars: Population II – stars: solar-type – white dwarfs

1. INTRODUCTION

It has long been realized that a large fraction of solar-type field stars are non-single and, since they are known to evolve on timescales comparable to the age of the Galaxy, one must expect that old binary stars with orbital periods of months or years sooner or later contact, once the more massive component evolves to a giant star and thereafter to a stellar remnant. This, in turn, may give rise to the birth of a bright blue straggler star for the formerly less massive component. In this contribution we present a plain textbook example for a system of this kind that in spite of its nearness and brightness has gone unnoticed for decades.

The system that will be discussed in this work has been known as a high-velocity star ever since Roman (1955) first published an extended list of such objects. As briefly described in Willmarth et al. (2016), there has been some dispute whether the star could have a companion; this was first claimed to be the case by Abt & Levy (1976). The controversy was only most recently solved by Katoh et al. (2013) and Willmarth et al. (2016) with a now well-established $P = 1144$ day orbit. Some evidence for an unseen companion, however, had already been in place for the last two decades with the *Hipparcos* astrometry (e.g., Makarov & Kaplan 2005).

Most remarkably, the relevant source—a bright F-type star in the southern sky—pretends to be as young as $\tau \simeq 2.3$ Gyr, and only upon closer inspection unveils its real nature as an ancient object. Yet, it is not a halo but a disk star, and it is not metal-poor but metal-rich. Its companion is found to be a white dwarf and the system, in fact, is found to be a most relevant messenger from the early starburst epoch when the Milky Way was in its infancy.

The present work discusses the remarkable aspects of a truly fascinating star that is found in the constellation *Libra* and where it has been given the number *49*.

2. OBSERVATION AND ANALYSIS

The observation on which this work is based refers to a single high-resolution, high signal-to-noise ratio spectrum of 49 Lib, secured on 2002 August 14 with the FEROS échelle spectrograph (Kaufer et al. 1999) at the La Silla Observatory in Chile. The reduction and analysis follows the usual procedures and methods as, for instance, described in Fuhrmann et al. (2011). The so-derived stellar parameters of 49 Lib are set out in Table 1.

3. IDENTIFICATION AS A POPULATION II BLUE STRAGGLER STAR

The odd nature of the bright F-type star 49 Lib is that it appears to be as young as $\tau \simeq 2.3$ Gyr, but at the same time is characterized by a space velocity that is very unlike a Population I star. If 49 Lib should truly be an old star, this must be documented in its chemistry, notably in terms of a low iron-to-magnesium abundance ratio, as the dominating nucleosynthesis product from massive stars in the very early epoch of the Milky Way.

The situation as it is found in the solar neighborhood is set out in Figure 1 for a complete sample of 401 solar-type stars within 25 pc (Fuhrmann et al. 2017). In the chemical abundance planes of this figure (left-hand panels), dark blue circles denote Population II stars, light blue circles are Population I stars, and asterisks refer to intermediate-disk stars. 49 Lib, given by the red symbol, is clearly identified as a Population II member. Actually, it is even more metal-rich than any of the template Population II stars. The Toomre diagram in the right-hand panel of Figure 1 displays the same template sample and provides unequivocal kinematical evidence for an old star, as discussed further above.

Table 1
Basic Stellar Parameters of 49 Lib Aa

$T_{\rm eff}$	6190 ± 80 K
$\log g$	3.93 ± 0.10 cgs
[Fe/H]	-0.11 ± 0.08 dex
[Fe/Mg]	-0.34 ± 0.05 dex
ξ_t	1.54 ± 0.20 km s^{-1}
$\zeta_{\rm RT}$	(fixed) 6.0 km s^{-1}
$v \sin i$	9.2 ± 0.4 km s^{-1}
V	5.467 ± 0.005 mag
$M_{\rm bol}$	2.64 ± 0.11 mag
BC_V	-0.09 ± 0.05 mag
Radius	2.24 ± 0.13 $R_\odot$
Mass	$1.55^{+0.07}_{-0.13}$ $M_\odot$
Nominal age	$2.3^{+0.7}_{-0.3}$ Gyr
True age	12 ± 1 Gyr

Note. The entries ξ_t and $\zeta_{\rm RT}$ denote the micro- and macroturbulent velocities, respectively. All given uncertainties represent 2σ errors.

An F-type star with an effective temperature $T_{\rm eff} = 6190$ K is certainly not compatible with an ancient Population II star (cf. Fuhrmann et al. 2017, Figure 4). In other words, 49 Lib is a field blue straggler, rejuvenated in a more recent mass transfer event.

4. THE CASE OF A WHITE DWARF COMPANION

With 49 Lib now being identified as a blue straggler star, one can ask about its origin. This could be, for instance, a former merger with a red dwarf, driven by orbital evolution from its known companion, just as it could be this very companion in the case of a stellar remnant, similar to the blue straggler stars in NGC 188 recently discussed by Gosnell et al. (2015).

Support for a significant mass transfer, albeit not necessarily from a degenerate, comes from the observation that 49 Lib Aa shows no lithium in its spectrum, unlike most stars of its effective temperature range. An example is given in Figure 2 in comparison to the $\tau \simeq 2.7$ Gyr F-type Population I star θ UMa A. We will come back to the significance of the lack of lithium in 49 Lib Aa in the next section.

More importantly, however, the spectroscopic orbit displays a fairly small $e = 0.11$ eccentricity (Katoh et al. 2013; Willmarth et al. 2016). Given the substantial orbital period $P = 1144$ day for 49 Lib, this is most plausibly understood as a signature of a former mass transfer from an evolved companion. With reference to the Rappaport et al. (1995) period—white dwarf mass relation

$$P_{\rm orb} \simeq 1.3 \times 10^5 M_{\rm WD}^{6.25} (1 + 4M_{\rm WD}^4)^{-3/2} (1 - e)^{-3/2},$$

we can say that if the companion is indeed a degenerate it must be a low-mass white dwarf with a fairly well-determined mass at $M_{\rm WD} \simeq 0.48$ $M_\odot$.

From the mass functions given in Katoh et al. (2013) and Willmarth et al. (2016) and with $M_{\rm BS} = 1.55^{+0.07}_{-0.13}$ $M_\odot$ that we derive (see below) for the F-type star, we get an orbital inclination $i = 141.3^{-1.0}_{+2.0}$ degree, in good agreement with the *Hipparcos* astrometric orbit derived by Willmarth et al. (2016) at $i = 143\overset{\circ}{.}0 \pm 2\overset{\circ}{.}0$. Hence, with reference to the latter value and with the given uncertainties, we get

$$M_{\rm WD} = 0.50^{+0.03}_{-0.04}\ M_\odot$$

for the mass of the unseen companion.

Undoubtedly, this is strong evidence for a white dwarf companion, but we can go a step further and demonstrate in the next section that 49 Lib is also an almost perfect textbook example for a mostly conservative mass transfer from a progenitor that once filled its Roche lobe.

5. A CONSERVATIVE MASS TRANSFER SCENARIO

What exactly happened to 49 Lib can be described in surprising detail to the extent that we already have detailed information on its true age, which must be at or even above 12 Gyr, as first demonstrated in Bernkopf et al. (2001) for nearby Population II subgiants. Given that 49 Lib is remarkably metal-rich at [Mg/H] = +0.23 and [Fe/H] = −0.11, one may find this extreme age intuitively surprising, but it is important to understand that neither stellar magnesium nor iron abundance have anything to do with the age of a star. Instead, the metal enrichment of a star depends on its environment at birth, whereas the age can be inferred from abundance ratios, set by the environment, such as, among others, the iron-to-magnesium abundance ratio.

Thus, the fairly precise age information on 49 Lib immediately provides us with a fairly precise constraint on the stellar mass of the initial primary (now white dwarf), as one can deduce from the VandenBerg et al. (2006) evolutionary tracks set out in Figure 3. With respect to these tracks one can assume that with a mass of less than 1.04 $M_\odot$ the initial primary would still be an ordinary star, whereas with a mass above 1.08 $M_\odot$ its transition to a stellar remnant likely took place too far in the past, in the sense, that the resulting blue straggler star would not show the significant rotational velocity that it does (cf. Table 1), and also simply because in about 0.5 Gyr the bright blue straggler component will itself turn into a white dwarf. In other words, apart from external uncertainties in the general modeling of stellar atmospheres and stellar interiors, Figure 3 suggests that the mass of the white dwarf progenitor of 49 Lib was likely constrained to $M = 1.06 \pm 0.02$ $M_\odot$.

With this initial mass and the present white dwarf mass, the former G-type primary most likely lost a mass $\Delta M = 1.06$–0.50 $M_\odot = 0.56$ $M_\odot$. For the former secondary (now the blue straggler) we can say that its initial mass could not have exceeded that of the initial primary, i.e., we get 1.03 $M_\odot$ as an upper mass limit, whereas for a mass below 0.97 $M_\odot$ it could become difficult to explain where the $M_{\rm BS} = 1.55^{+0.07}_{-0.13}$ $M_\odot$ mass for the present F-type star should come from.

We summarize this mass transfer scenario in Table 2, from which it becomes clear that essentially all transferred mass of the 49 Lib system must have been transferred conservatively among its components, the only caveat being that the resulting blue straggler mass is less accurate on account of the fact that it is placed in the hook region in Figure 3 (see the red circle with its associated 2σ error bars).

At this point, we briefly come back to the observed lack of lithium in 49 Lib Aa in Figure 1, which, as Figure 3 now suggests (see also Fuhrmann et al. 2012a, Figure 4), can easily be explained with its early G-type main-sequence evolution.

Following Refsdal & Weigert (1971), a conservative mass transfer for 49 Lib would then have started with two $M = 1.06 + 1.00$ $M_\odot$ G-type stars, as explained above, with an initial orbital period $P \simeq 468$ day and semimajor axis $a \simeq 323$ $R_\odot$. Once the mass transfer started, this first led to a slight reduction of the system size at $a \simeq 322$ $R_\odot$, and then an increase

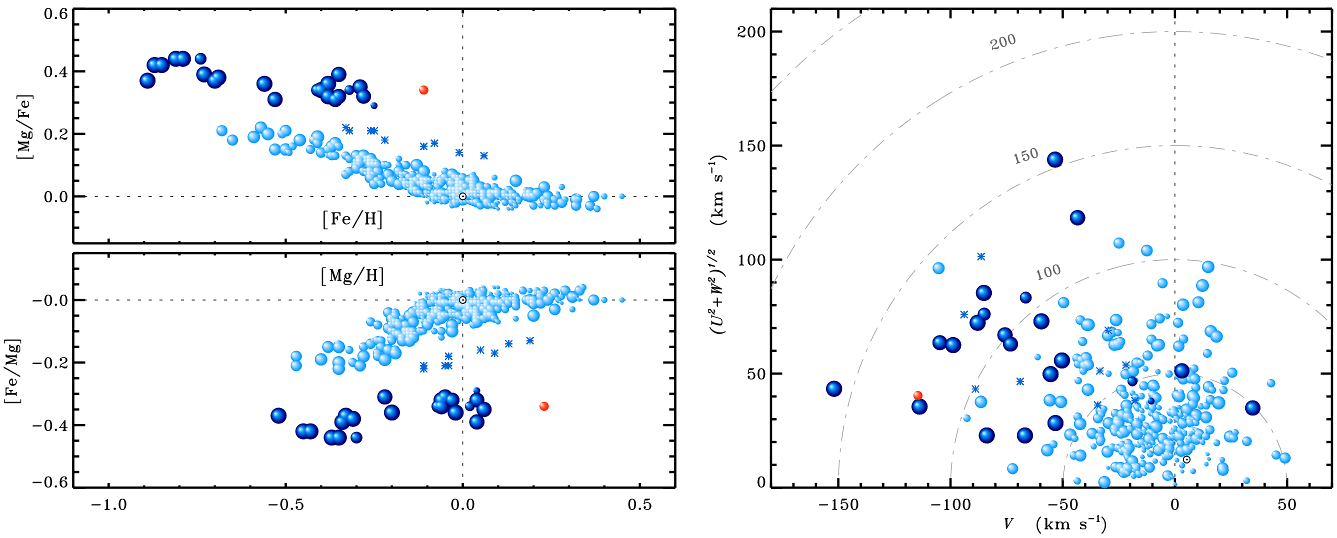

Figure 1. Left: iron and magnesium abundance ratios of a volume-complete template sample of 401 local F-, G-, and K-type stars. Dark blue circles denote Population II stars, light blue circles are Population I stars, and asterisks refer to intermediate-disk stars. Circle diameters are in proportion to the stellar age estimates. Right: Toomre diagram of the peculiar space velocities for the same template. The dashed–dotted curves delineate constant peculiar space velocities $v_{\rm pec} = (U^2 + V^2 + W^2)^{1/2}$ in steps of $\Delta v_{\rm pec} = 50$ km s^{-1} and with respect to the local standard of rest. In both panels, the red symbol denotes the extremely metal-rich Population II blue straggler 49 Lib. The position of the Sun ($\odot$) is also given.

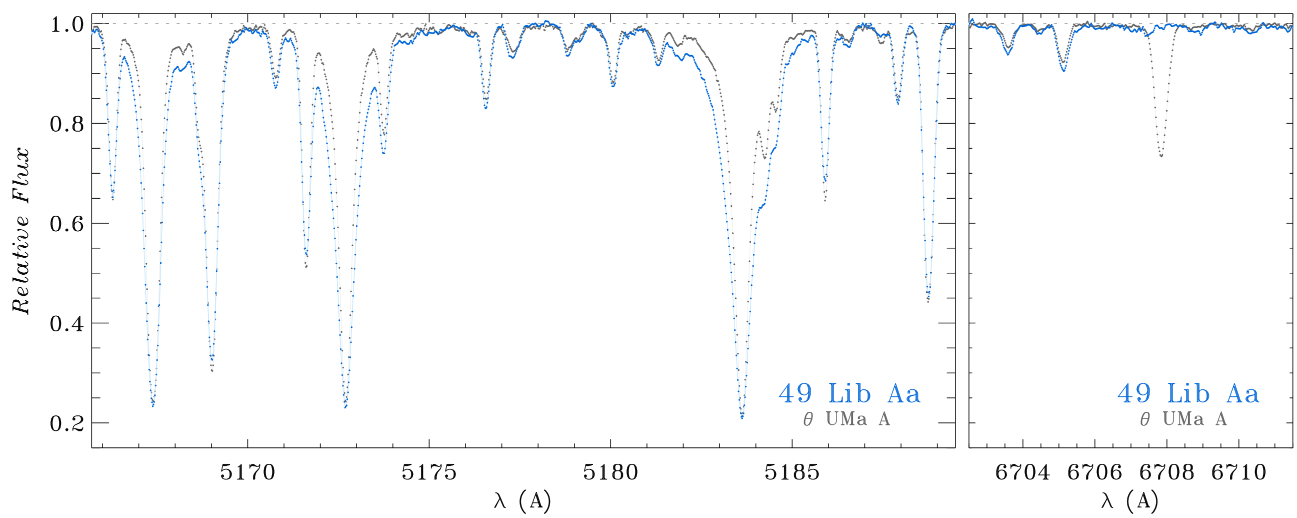

Figure 2. High-resolution spectra of the F-type stars 49 Lib Aa and θ UMa A in the region around the prominent Mg Ib triplet lines (left) and for the Li I λ6707 Å resonance doublet (right). The $\tau \simeq 2.7$ Gyr old Population I star θ UMa A at $T_{\rm eff}/\log g/[{\rm Fe/H}] = 6243/3.80/-0.18$ and $v \sin i = 6.8$ km s^{-1} has similar stellar parameters compared to 49 Lib Aa, but less magnesium at [Fe/Mg] $= -0.10$, clearly visible in the left-hand panel. The fact that the blue straggler Population II star 49 Lib Aa displays no lithium in its spectrum is due to its origin as a less massive $M = 1.00 \pm 0.03$ $M_\odot$ and cooler G-type star.

to the present $P = 1144$ day orbital period and semimajor axis $a = 585$ $R_\odot$.

Note that with a more compact initial orbit, a system like 49 Lib could principally also account for an even more massive A-type blue straggler, as they have been observed at large distances from the Galactic plane and away from known star forming regions. Except for more diverse higher level systems, any Population II blue straggler binary would, however, be confined to $M_{\rm BS} \leqslant 2.0$ $M_\odot$.

We conclude this section by pointing out the following: as a Population I star with a range of possible ages up to 8 Gyr, we would observe a star like 49 Lib always as an ordinary pair of G-type stars. Within about 0.5 Gyr, however, 49 Lib may likely become a double-degenerate. In this sense, we are lucky to see this ancient star in its final accelerated few per cent “bright time,” before it will start contributing in its forthcoming “dark time” to the high mass-to-light ratio of its ancient parent population. As one can imagine, there are likely many descendants of this kind in the solar neighborhood. Yet, and provided the architecture of the 49 Lib system continues to favor a conservative mass transfer in its future evolution, 49 Lib could also serve as an excellent progenitor system for a type Ia supernova. Since the F-type star would then becomes as well a $M_{\rm WD} = 0.50$ $M_\odot$ white dwarf, its $\Delta M = 1.55$–0.50 $M_\odot = 1.05$ $M_\odot$ mass loss could not be simply accreted by its white dwarf companion.

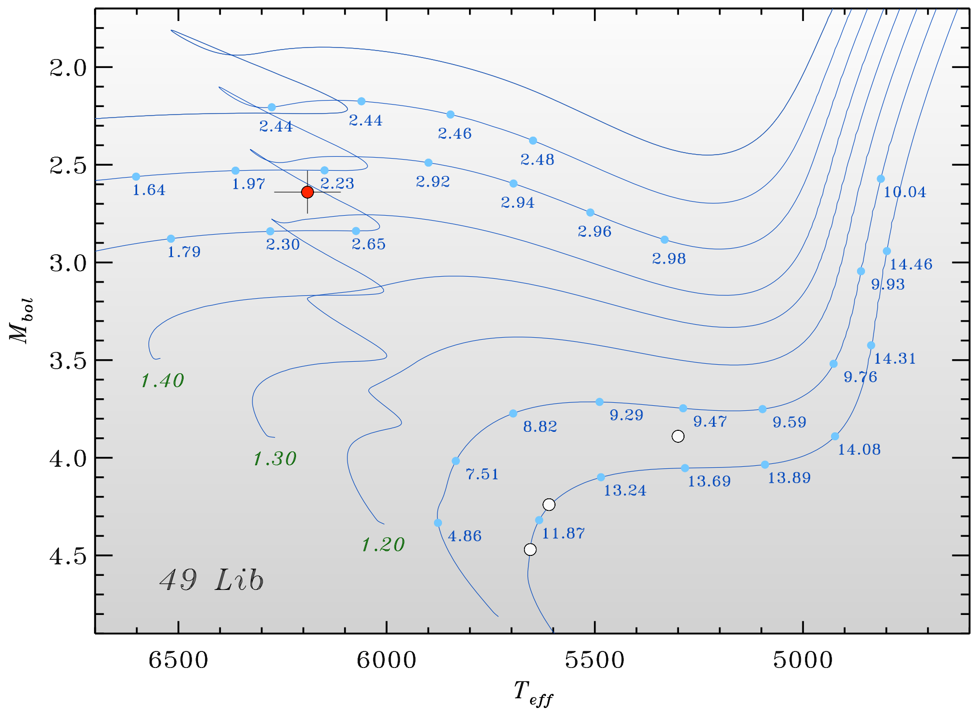

Figure 3. VandenBerg et al. (2006) evolutionary tracks for stellar masses $M = 1.0, 1.1, 1.2, ..., 1.7\ M_\odot$ and abundances [Fe/H] = −0.11 and [Fe/α] = −0.30, as approximately measured for the Population II blue straggler 49 Lib Aa. Small numbers denote ages in Gyr. The red circle represents the current position of 49 Lib Aa, rejuvenated from its degenerate companion to a purported age of $\tau \simeq 2.3$ Gyr. Two white circles on the lowermost $M = 1.0\ M_\odot$ track illustrate the likely position of the former G-type secondary (now the F-type blue straggler) at ages of 11.5 and 12.0 Gyr, slightly before the mass transfer epoch. The former G-type primary (now white dwarf), in turn, is given by the white circle at $T_{\rm eff} = 5300$ K on a $M = 1.06\ M_\odot$ track at 11.5 Gyr. For the 49 Lib system the age and mass constraints are such that one must assume an essentially conservative mass transfer (see the text for details).

Table 2
49 Lib Mass Transfer Scenario

Initial Components	Initial Mass ($M_\odot$)	Mass Lost ($M_\odot$)	Mass Received ($M_\odot$)	Present Components
G-type primary	1.06 ± 0.02	$0.56^{+0.02}_{-0.02}$	⋯	low-mass white dwarf
G-type secondary	1.00 ± 0.03	⋯	$0.55^{-0.03}_{+0.03}$	F-type blue straggler

Note. The deduced masses imply a mostly conservative mass transfer for this system.

6. ON THE METAL ENRICHMENT OF 49 LIB

Apart from the fact that 49 Lib is a remarkable ancient mass transfer system whose former evolution we can track with high accuracy, it is also a very remarkable source in terms of its metal enrichment, as demonstrated in Figure 1. In our recent work on the nearby stars (Fuhrmann et al. 2017) we have pointed out that, in view of the given mass–metallicity relation of galaxies at high redshift (Erb et al. 2006), the super-solar magnesium enrichment levels that we observe for part of the Populaton II stars necessarily imply that this ancient population must be a substantial contributor to the Galactic mass. This is supported by the 20% local normalization that we derived for Population II stars, as is also supported from the even higher normalization for degenerate stars of this population (Fuhrmann et al. 2012b), and thus confirms the early conclusion already found by Kuijken & Gilmore (1991) that locally there is no need for non-baryonic dark matter.

While 49 Lib is presumably not typical in regard to its metal enrichment for the local Population II, it nevertheless demonstrates how far one can get with ancient disk stars. Note in particular, that in terms of its magnesium abundance 49 Lib is more metal-rich than most of the much younger Population I stars in Figure 1. The nearby bright blue straggler star 49 Lib thus adds important key information in terms of our notions of the early epoch when the Milky Way came into being.

Based on data products from observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 069.D-0711(A). We are grateful to the anonymous reviewer for constructive comments. KF acknowledges support from the DFG grant FU 198/11-1.

REFERENCES

Abt, H. A., & Levy, S. G. 1976, ApJS, 30, 273
Bernkopf, J., Fiedler, A., & Fuhrmann, K. 2001, in ASP Conf. Ser. 245, Astrophysical Ages and Time Scales, ed. T. von Hippel, C. Simpson, & N. Manset (San Francisco, CA: ASP), 207
Erb, D. K., Shapley, A. E., Pettini, M., et al. 2006, ApJ, 644, 813

Fuhrmann, K., Chini, R., Haas, M., et al. 2012a, ApJ, 761, 159
Fuhrmann, K., Chini, R., Hoffmeister, V. H., et al. 2011, MNRAS, 411, 2311
Fuhrmann, K., Chini, R., Hoffmeister, V. H., & Bernkopf, J. 2012b, MNRAS, 420, 1423
Fuhrmann, K., Chini, R., Kaderhandt, L., & Chen, Z. 2017, MNRAS, 464, 2610
Gosnell, N. M., Mathieu, R. D., Geller, A. M., et al. 2015, ApJ, 814, 163
Katoh, N., Itoh, Y., Toyota, E., & Sato, B. 2013, AJ, 145, 41
Kaufer, A., Stahl, O., Tubbesing, S., et al. 1999, Msngr, 95, 8
Kuijken, K., & Gilmore, G. 1991, ApJL, 367, L9
Makarov, V. V., & Kaplan, G. H. 2005, AJ, 129, 2420
Rappaport, S., Podsiadlowski, P., Joss, P. C., et al. 1995, MNRAS, 273, 731
Refsdal, S., & Weigert, A. 1971, A&A, 13, 367
Roman, N. G. 1955, ApJS, 2, 195
VandenBerg, D. A., Bergbusch, P. A., & Dowler, P. D. 2006, ApJS, 162, 375
Willmarth, D. W., Fekel, F. C., Abt, H. A., & Pourbaix, D. 2016, AJ, 152, 46