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Letter to the Editor

BD+43° 3654 – a blue straggler?

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ABSTRACT

The astrometric data on the runaway star BD+43° 3654 are consistent with the origin of this O4If star in the center of the Cyg OB2 association, while BD+43° 3654 is younger than the association. To reconcile this discrepancy, we suggest that BD+43° 3654 is a blue straggler formed via a close encounter between two tight massive binaries in the core of Cyg OB2. A possible implication of this suggestion is that the very massive (and therefore apparently very young) stars in Cyg OB2 could be blue stragglers as well. We also suggest that the binary-binary encounter producing BD+43° 3654 might be responsible for ejection of two high-velocity stars (the stripped helium cores of massive stars) – the progenitors of the pulsars B2020+28 and B2021+51.

Key words. stars: kinematics – pulsars: individual: PSR B2020+28 – open clusters and associations: individual: Cyg OB2 – stars: individual: BD+43° 3654

1. Introduction

BD+43° 3654 is a massive (O4If) runaway star located $\sim 2\overset{\circ}{.}7$ northeast of the Cyg OB2 association (Comerón & Pasquali 2007). The astrometric data on BD+43° 3654 suggest that this star was ejected from the center of Cyg OB2 ~1.8 Myr ago (Comerón & Pasquali 2007). BD+43° 3654 is one of the three known very massive ($\gtrsim 60\,M_\odot$) runaway stars (the two other stars are ζ Pup and λ Cep) whose high ($\gtrsim 40$ km s^{-1}) peculiar velocities cannot be explained within the framework of the binary-supernova scenario (see Sect. 3). The more likely channel for production of these high-velocity massive objects is through dynamical processes in the dense cores of young massive star clusters (Poveda et al. 1967; Leonard & Duncan 1990), particularly through close encounters between tight massive binary stars (Mikkola 1983; Leonard & Duncan 1990). The most common outcome of binary-binary encounters is the exchange of the more massive binary components into a new eccentric binary or a single merged star and ejection of the less massive ones with high velocities (e.g. Leonard 1995). The ejection velocity of the lightest components could be as high as the escape velocity from the surface of the most massive star in the binaries (i.e. ~1000 km s^{-1}; Leonard 1991). Correspondingly, the recoil velocity of the newly formed object (the massive binary or the merged star) could significantly exceed the escape velocity from the potential well of the parent cluster, so that this object becomes a runaway.

In this Letter we suggest that BD+43° 3654 is a merged star formed via a close encounter between two tight massive binaries in the core of Cyg OB2 (cf. Leonard 1995). We suggest that BD+43° 3654 is a blue straggler, i.e. a rejuvenated star with the apparent age smaller than the age of the parent association (see Sects. 2 and 4). The high linear momentum imparted to BD+43° 3654 implies that the binary-binary encounter was very energetic and that the lower mass components of the binaries involved in the encounter were ejected with high velocities.

Interestingly, Cyg OB2 may be associated with the origin of two high-velocity pulsars, PSR B2020+28 and PSR B2021+51. The high-precision proper motion and parallax measurements for these pulsars (presently separated by ~23°) lead to the suggestion that they originated ~1.9 Myr ago within several parsecs of each other in the direction of Cyg OB2 (Vlemmings et al. 2004). Vlemmings et al. (2004) believe that the progenitors of both pulsars were members of a common binary and that the pulsars were separated at the birth of the second one, following asymmetric supernova explosion. An alternative possibility is that the pulsars were separated before their birth, and that they are the remnants of runaway stars ejected from Cyg OB2 due to the dynamical three- or four-body encounters (Gvaramadze 2007, Paper I). The relative position of the pulsars and BD+43° 3654 on the sky and the similarity between their kinematic ages suggest that the three objects might be ejected from Cyg OB2 via the same dynamical event – the close encounter between two massive binaries (Sect. 4; cf. Gies & Bolton 1986; Hoogerwerf et al. 2001; Gualandris et al. 2004).

2. BD+43° 3654 and Cyg OB2

The isochronal age of BD+43° 3654, derived by Comerón & Pasquali (2007) from the position of this O4If star in the Hertzsprung-Russell (HR) diagram and the isochrones from the evolutionary models for massive stars by Meynet et al. (1994), is similar to the kinematic age (i.e. the time since the ejection of the star from Cyg OB2). Both ages should be compared with the age of the parent association of ~1−5 Myr (e.g. Bochkarev & Sitnik 1985; Torres-Dodgen et al. 1991; Herrero et al. 1999; Hanson 2003; Knödlseder 2003). The wide age spread could be considered as an indication that the star formation in Cyg OB2 is non-coeval (Massey & Thompson 1991; Hanson 2003). On the other hand, the youngest ages of $\lesssim 3$ Myr come from the presence in Cyg OB2 of a two dozen early type O stars, while the evolutionary status of the less massive stars in the association is consistent with an age of 4−5 Myr (the situation typical of young massive star clusters and associations; e.g. Massey 2003). One can hypothesize that the actual age of Cyg OB2 is ~4−5 Myr and that the most massive (and therefore apparently the youngest) stars in the association are in fact the rejuvenated stars (blue stragglers) formed via merging of less massive stars in the course of close binary-binary encounters ~2 Myr ago, when Cyg OB2 was much more compact (see below). In our reasoning we proceed from the results of binary-binary scattering experiments by Leonard (1995), which showed that about half of the merged stars formed via close encounters between binaries remain bound to the parent cluster (some of them form binaries with another blue straggler) and appear much younger than other members of the cluster (see also Portegies Zwart et al. 1999).

An indirect support for our hypothesis comes from the recent study of early-A stars in the direction of Cyg OB2 by Drew et al. (2008). This study revealed several hundred A stars within the boundaries of the association and suggested that the age of these stars is ≥5 Myr, provided that they are located at a distance of ≤1.7 kpc (i.e. at the distance of Cyg OB2; Kiminki et al. 2007; cf. Torres-Dodgen et al. 1991; Massey & Thompson 1991). The age of ~3−5 Myr would also be required if: (i) the pulsars B2020+28 and B2021+51 indeed originate in Cyg OB2 (Paper I; see also Sect. 4); (ii) the HEGRA TeV source observed in the direction of Cyg OB2 (Aharonian et al. 2002) is related to a young pulsar in the association (Bednarek 2003); and (iii) a partially nonthermal shell-like object coincident with the HEGRA source is a supernova remnant (Butt et al. 2008).

Moreover, the stellar content of Cyg OB2 could be contaminated by young massive stars injected into the association from nearby associations (Uyaniker et al. 2001) and the numerous young clusters around Cyg OB2[1] (Dutra & Bica 2001; Comerón & Torra 2001; Le Duigou & Knödlseder 2002). In the latter case, some of the "alien" O stars can be produced through merging of two or three stars in the course of binary-binary encounters in clusters of B-type stars (see Leonard 1995). For example, in our search for bow shocks around Cyg OB2 (Gvaramadze & Bomans, in preparation), we discovered a bow shock produced by one of the early-type stars from the list of new members of the association by Comerón et al. (2002). This star (designated by Comerón et al. 2002, as A37) was classified by Hanson (2003) as a O5V star, and therefore it should be a young (≲1 Myr) object. The photometric distance to this star of 1.7−1.8 kpc (derived with use of the *UBVJHK* synthetic photometry of Galactic stars by Martins & Plez 2006) is consistent with the distance to Cyg OB2. The astrometric data on the star and the geometry of the bow shock, however, suggest that this high-velocity (~120 km s^{-1}) runaway was ejected either from the young cluster embedded in the H II region DR 15 (located on the border of Cyg OB2 ~1° west of the current position of the star) or from the open cluster NGC 6913 (centered ~3.°4 west of the star).

At the distance to Cyg OB2 of ~1.7 kpc, the peculiar (transverse) velocity of BD+43° 3654 is ≃40 ± 10 km s^{-1} (we used here the Galactic constants $R_0 = 8$ kpc and $\Theta_0 = 200$ km s^{-1} (e.g. Reid 1993; Kalirai et al. 2004; Avedisova 2005) and the solar peculiar motion $(U_\odot, V_\odot, W_\odot) = (10.00, 5.25, 7.17)$ km s^{-1} (Dehnen & Binney 1998); cf. Comerón & Pasquali (2007)). The position of BD+43° 3654 in the HR diagram and the evolutionary tracks by Meynet et al. (1994) imply an initial mass of the star of ≃70 ± 15 $M_\odot$ (Comerón & Pasquali 2007). The high linear momentum attained by this runaway star could be used to constrain the possible mechanisms of its origin. In Sect. 3 we show that runaways of this mass and velocity are unlikely to be produced via the disruption of a binary due to the (asymmetric) supernova explosion (the binary-supernova scenario; Blaauw 1961; Stone 1991). Another possibility is that this star attained a high peculiar velocity via the strong dynamical three- or four-body encounter (the dynamical ejection scenario; Poveda et al. 1967; Gies & Bolton 1986). In Sect. 4, we suggest that the most likely path for the origin of BD+43° 3654 is through the close encounter between two tight massive binaries.

Cyg OB2 is one of the most compact and massive associations in the Milky Way. It contains ~100 O stars or stars with O-type progenitors (Knödlseder 2000; Comerón et al. 2002). The half light radius of Cyg OB2 is ~6 pc (Knödlseder 2000). Assuming that the association expands with a velocity equal to its velocity dispersion (~2.4 km s^{-1}; Kiminki et al. 2007), one finds that the majority of massive stars in Cyg OB2 were originally concentrated in a region of radius of <1 pc (that is consistent with the observation that the initial radii of young clusters are ≲1 pc; Kroupa & Boily 2002). It is therefore plausible that at the moment of ejection of BD+43° 3654 the stellar number density in the core of Cyg OB2 was high enough to ensure that close encounters between its constituents were frequent. The necessary condition for effective production of runaways is a high binary fraction among massive stars. The recent radial velocity survey of Cyg OB2 by Kiminki et al. (2007) gives a lower limit on the massive binary fraction of 30−40%, while the comparison of the data from the survey with the expectations of the Monte Carlo models suggest that this fraction could be ≥80% (Kobulnicky & Fryer 2007). Thus we believe that ~2 Myr ago the conditions in the core of Cyg OB2 were favourable for the dynamical processes discussed in Sect. 4.

3. BD+43° 3654: binary-supernova scenario

According to the binary-supernova scenario, a massive star residing in a binary system could attain a high peculiar velocity due to the disruption of the binary after the companion star exploded as a supernova (Blaauw 1961; Stone 1991). We show that the peculiar velocity of BD+43° 3654 cannot be accounted for within the framework of this scenario (cf. Vanbeveren et al. 2007).

The kinematic age of BD+43° 3654 of ~1.8 Myr and the minimum possible lifetime of the supernova progenitor star of ~2.5−3 Myr imply that the actual age of BD+43° 3654 should be ≳4.5−5 Myr. The discrepancy between the "observed" and the inferred ages could be reconciled if BD+43° 3654 is a rejuvenated star. For example, it could be rejuvenated through mass transfer from the primary star during the Roche lobe overflow stage (e.g. Dray & Tout 2007). In this case, the effect of rejuvenation would be significant only if the mass gained by the rejuvenated star was larger than its initial mass. Although one cannot exclude this possibility, we note that stars more massive than ~40 $M_\odot$ could lose a significant fraction of their mass via the heavy stellar wind and the Roche lobe overflow will not occur (Vanbeveren et al. 1998). Another possibility is that BD+43° 3654 was formed in the course of a close encounter between two massive binaries, during which two stars of the binaries merged into a single rejuvenated star (now BD+43° 3654)

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[1] A study of the Cygnus X region by Schneider et al. (2006) suggests that these clusters and the Cyg OB2 and OB9 associations form a coherent complex and that formation of the clusters was triggered by the effect of massive stars in the associations (cf. Le Duigou & Knödlseder 2002).

and caught a third (more massive or more evolved) star to form a new binary, while the fourth star was ejected as single (cf. Leonard 1995).

Let us assume that at the moment of supernova explosion in a binary system the mass of the second star was 70 $M_\odot$. It is obvious that to disrupt such a massive system, the explosion should be asymmetric so that the supernova stellar remnant attained a kick. In this case, the stellar remnant can impart some momentum to the companion star in the course of disintegration of the binary (Tauris & Takens 1998). The magnitude of the momentum depends on the angle between the kick vector and the direction of motion of the exploding star and reaches its maximum for a certain value of the angle (given by Eq. (4) in Gvaramadze 2006). One can show that to accelerate a star as massive as BD+43° 3654 to the velocity of 40 km s^{-1}, the kick direction should be very carefully tuned (i.e. should be within several degrees of the direction towards the companion star), while the magnitude of the kick should be very large ($\geq$700 km s^{-1}, if the stellar remnant is a neutron star, or $\geq$200 km s^{-1}, if the remnant is a black hole of mass $\sim$5 $M_\odot$). Although one cannot exclude this possibility, we consider it as highly unlikely (cf. Gvaramadze 2006; Paper I).

4. BD+43° 3654: dynamical ejection scenario

The numerical experiments by Leonard (1995) showed that a significant fraction of unbound blue stragglers (formed via binary-binary encounters in dense clusters) attain peculiar velocities large enough ($\geq$30 km s^{-1}) to be classified as runaways. It is therefore tempting to consider the possibility that BD+43° 3654 is a blue straggler formed through an encounter between two tight massive binaries. The most common outcome of encounters between such binaries is the exchange of the more massive components into a new eccentric binary or a single merged star and ejection of the less massive ones with high velocities. The binary would ultimately coalesce into a single star if its orbit is sufficiently compact.

Let us assume that BD+43° 3654 is the result of a merging of two main-sequence (MS) stars of mass M_1 and M_2 ($M_1 \geq M_2$) and of the same age $t_{\rm merg} \simeq 3$ Myr. Under these assumptions, the merger product is also an MS star (of mass $M_* \simeq M_1 + M_2$), and its new age is given by (see Meurs & van den Heuvel 1989; Portegies Zwart et al. 1999):

$$t_* \sim \frac{M_1}{M_*} \frac{t_{\rm MS}(M_*)}{t_{\rm MS}(M_1)} t_{\rm merg}, \tag{1}$$

where $t_{\rm MS}$ (M_*) and $t_{\rm MS}(M_1)$ are the MS lifetimes of stars of mass M_* and M_1. One can consider two cases: (i) BD+43° 3654 is the product of a physical collision of two stars during the close binary-binary encounter; and (ii) BD+43° 3654 is the result of coalescence of two stars in a close binary system. In the first case, one should require that $t_* \sim 0$, since the current (apparent) age of BD+43° 3654, $t = t_* + t_{\rm kin}$, is comparable to its kinematic age $t_{\rm kin} \simeq 1.8$ Myr. This requirement could be fulfilled only if the encounter between binaries occurs very soon after their birth in the association (i.e. $t_{\rm merg} \sim 0$ Myr), which contradicts our assumption that $t_{\rm merg} \sim 3$ Myr. Note, however, that here we neglected the possibility that the colliding stars were already rejuvenated through mass transfer in the original tight binaries so that their apparent age was much less than the actual one. In the second case, one can assume that the binary components coalesced into a single star only recently, i.e. the time elapsed since the formation of BD+43° 3654 is less than the kinematic age of the binary. As an example, suppose that the runaway binary consists of two stars of mass $\sim$35 $M_\odot$. For $t_{\rm MS}$ (35 $M_\odot$) $\simeq$ 4.5 Myr and $t_{\rm MS}$ (70 $M_\odot$) $\simeq$ 2.5 Myr (Meynet & Maeder 2003), and assuming that the binary merged $\sim$1 Myr after ejection from Cyg OB2 (i.e. $t_{\rm merg} \sim 4$ Myr), one has from Eq. (1) that $t_* \sim 1.1$ Myr. During the next $\sim$0.7 Myr ($=t_{\rm kin} - t_*$), the merged star evolves into a blue supergiant with parameters similar to those of BD+43° 3654 [see the evolutionary tracks by Meynet et al. (1994) and the calibration of parameters of Galactic O stars by Martins et al. (2005)].

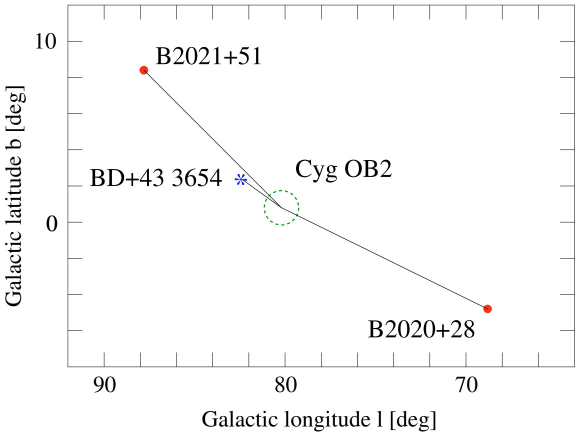

Fig. 1. Relative position of BD+43° 3654 and the pulsars PSR B2020+28 and PSR B2021+51 on the sky. The circle of angular diameter of 2° indicates the boundaries of the Cyg OB2 association.

In Sect. 1, we mentioned that the origin of two pulsars, B2020+28 and B2021+51, could be associated with Cyg OB2. In Paper I, we suggested that these pulsars are the remnants of runaway stars ejected (with velocities similar to those of the pulsars) from Cyg OB2 due to the dynamical three- or four-body encounters. Our suggestion was based on the recently recognized fact that the high-velocity pulsars could be the descendants of high-velocity runaway stars (i.e. the peculiar velocities of pulsars do not necessarily originate from asymmetric supernova explosions; Paper I; Gvaramadze et al. 2008). Strong support for this possibility comes from the discovery of early B-type stars moving with velocities of $\sim$500–700 km s^{-1} (Edelmann et al. 2005; Przybilla et al. 2008; Heber et al. 2008). In Paper I, we used the similarity between the spin-down and the kinematic ages of B2020+28 and B2021+51 to suggest that their progenitors were the short-lived (<1 Myr) helium cores of massive stars, while from the age of Cyg OB2 at the moment of ejection of the helium cores ($\sim$3 Myr) we inferred that the zero-age MS masses of the ejected stars were $\geq$50–60 $M_\odot$; it is believed that stars of this initial mass could leave behind a neutron star (see Woosley et al. 1995; Muno et al. 2006; Bibby et al. 2008). The relative position of the pulsars and BD+43° 3654 on the sky (see Fig. 1) and the similarity between their kinematic ages suggest that the three objects might have had a common origin in the close encounter between two massive binaries. Below, we discuss this possibility in detail.

The (transverse) recoil velocity attained by the merged star is given by:

$$V_{*,\rm tr} = M_*^{-1} \left[(m_1 v_{1,\rm tr})^2 + (m_2 v_{2,\rm tr})^2 + 2 m_1 m_2 v_{1,\rm tr} v_{2,\rm tr} \cos\alpha\right]^{1/2}, \tag{2}$$

where m_1, m_2 and $v_{1,\rm tr}, v_{2,\rm tr}$ are, respectively, the masses and the transverse velocities of the helium cores (the progenitors of the pulsars) and α is the angle between the ejection velocity vectors of the helium cores. We assume that the pulsars did not received (significant) kicks at birth and therefore move (almost) in the same direction as their progenitors. Adopting that the binary-binary encounter occured 1.8 Myr ago and neglecting the effect of the Galactic gravitational potential, one obtains the transverse velocities of B2020+28 and B2021+51 as $\upsilon_{1,\rm tr} \simeq 200$ km s^{-1} and $\upsilon_{2,\rm tr} \simeq 170$ km s^{-1}, and $\alpha \simeq 160°$. Using Eq. (2), one can show that to explain the "observed" transverse velocity of BD+43° 3654 of 40 km s^{-1}, the progenitor of B2021+51 should already lose most of its mass via the stellar wind, i.e. by the moment of binary-binary collision m_2 should be several times smaller than m_1. For $M_* = 70 \pm 15\ M_\odot$ and assuming that $m_1 = (3{-}4)m_2$, one has from Eq. (2) that $m_1 \simeq (17{-}19) \pm 4\ M_\odot$ (i.e. a quite reasonable figure). For the above parameters, one finds that the velocity vector of the recoiled merged star is somewhat misaligned ($\sim$10°) to the residual velocity vector of BD+43° 3654. To explain this misalignment, one can assume that Cyg OB2 has a peculiar (transverse) velocity of $\sim$7 km s^{-1} in the northwest direction (cf. Hoogerwerf et al. 2001). The origin of peculiar velocity of this magnitude (typical of the OB associations near the Sun; de Zeeuw et al. 1999) could be understood if formation of Cyg OB2 was triggered by the collision between two molecular clouds (cf. Schneider et al. 2006).

One can also constrain the radial velocity of BD+43° 3654 using the parallactic distances to B2020+28 and B2021+51, respectively, of $2.7^{+1.3}_{-0.7}$ and $2.0^{+0.3}_{-0.2}$ kpc (Vlemmings et al. 2004). Taken at face value, these distances imply the pulsar radial velocities $\upsilon_{1,\rm r} \simeq 530^{+690}_{-370}$ km s^{-1} and $\upsilon_{2,\rm r} \simeq 160^{+160}_{-110}$ km s^{-1}, while from the conservation of the linear momentum one has $V_{*,\rm r} \simeq -(150^{+200}_{-110})$ km s^{-1}. The peculiar radial velocity of Cyg OB2 of $\simeq -6$ km s^{-1} (derived from the mean systemic velocity of the association of $\simeq -10$ km s^{-1}; Kiminki et al. 2007) only slightly changes the above figures. Our scenario for the origin of BD+43° 3654 therefore suggests that the radial component of the peculiar velocity of this star should be negative and at least as large as the transverse one. It could be that the radial velocity measurements for BD+43° 3654 will invalidate our scenario, so that the origin of the runaway star and the pulsars would not be related to each other. Even in this case, we believe that the origin of BD+43° 3654 should be accompanied by the ejection of two high-velocity stars, either early type B-stars or stripped helium cores of the more massive stars.

Thus, we suggest that the runaway massive star BD+43° 3654 originate from a close encounter between two binaries, originally consisting of a $\sim$35 and a $\sim$50–60 $M_\odot$ star. The more massive stars in each system evolved for $\sim$3 Myr, losing most of their mass, becoming helium stars. At this point, the binaries interacted, ejecting the helium stars at high velocity and resulting in the merger or near-merger of the 35 $M_\odot$ stars into a 70 $M_\odot$ star, which recoiled at a proportionally lower velocity. The more massive object is now seen as a blue straggler O4If star, while the helium stars exploded as supernovae soon after the ejection and produced the pulsars with a small or no kick at birth.

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