On the possible generation of the young massive open clusters Stephenson 2 and BDSB 122 by $\omega$ Centauri

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ABSTRACT

Context. A massive objects such as a globular cluster passing through the disk of a galaxy can trigger star formation.

Aims. We test the hypothesis that the most massive globular cluster in the Galaxy, $\omega$ Centauri, which crossed the disk approximately $24 \pm 2$ Myr ago, may have triggered the formation of the open clusters Stephenson 2 and BDSB 122.

Methods. The orbits of $\omega$ Centauri, Stephenson 2 and BDSB 122 are computed for the three-component model of Johnston, Hernquist & Bolte, which considers the disk, spheroidal and halo gravitational potentials.

Results. With the re-constructed orbit of $\omega$ Centauri, we show that the latest impact site is consistent, within important uncertainties, with the birth-site of the young massive open clusters BDSB 122 and Stephenson 2. Within uncertainties, this scenario is consistent with the time-scale of their backwards motion in the disk, shock wave propagation and delay for star formation.

Conclusions. Together with open cluster formation associated to density waves in spiral arms, the present results are consistent with the idea that massive globular clusters as additional progenitors of open clusters, the massive ones in particular.

Key words. Galaxy: globular cluster: individual: $\omega$ Centauri; Galaxy: open clusters and associations: individual: BDSB 122 and Stephenson 2

1. Introduction

Disk-stability criteria and impact assumptions suggest that the passage of a globular cluster (GC) can trigger a bubble or wave of self-propagating star formation within the disk of the Galaxy ([Wallin, Higdon & Staveley-Smith] 1996). The initial mechanical perturbation produces a local enhancement of the interstellar medium (ISM) density, from which localised star formation may occur. Subsequently, clustered star formation may happen along the border of a radially expanding density wave or ionisation front (e.g. Soria et al. 2003 – hereafter SCP05; Elmegreen & Lada 1977; Whitworth et al. 1994). The expanding bubble is capable of compressing the neutral ISM above the stability criterion against gravitational collapse. Alternative star-formation triggering mechanisms are the infall of a high-velocity HI cloud (Elmegreen, Efremov & Larsen 2000; Larsen et al. 2002), or hypernova explosions (Paczynski 1998).

Prominent, isolated star-forming bubbles have been observed in external galaxies. A bubble with $\approx 600$ pc in diameter was detected in NGC 6946 (Larsen et al. 2002), containing a young super star cluster and at least 12 surrounding young clusters, the latter being comparable to the most luminous Galactic OCs. The triggering mechanism in NGC 6946 appears to be the impact of a high-velocity HI cloud and/or hypernova explosions (Elmegreen, Efremov & Larsen 2000). The Galaxy may harbour similar structures. A possible example is the Cygnus superbubble, which contains OB associations (Vlemmings, Cordes & Chatterjee 2004, and references therein).

For a GC, the triggering effects are essentially gravitational. A natural assumption is that GCs, crossing the disk every 1 Myr on average, may be responsible for some star formation. A possible case relates the origin of the OC NGC 6231 to the GC NGC 6397 disk-crossing (Rees & Cudworth 2003). Another possibility is the low-mass GC FSR 584 as star-formation trigger in the W 3 complex (Bica et al. 2007).

The OCs Stephenson 2 and BDSB 122 were discovered in 1990 (Stephenson 1990) and 2003 (Bica et al. 2003), respectively. 2MASS (www.ipac.caltech.edu/2mass/releases/allsky) images of both clusters are shown in Fig. 1. The suspected richness of Stephenson 2 in red supergiants was confirmed by Nakaya et al. (2001) and Ortolani et al. (2002), providing an age of $\approx 20$ Myr, and a distance from the Sun $d_\odot = 6$ kpc (Ortolani et al. 2002). Both clusters are among the most massive OCs known in the Galaxy. Indeed, BDSB 122 has 14 red supergiants, is located at $d_\odot = 5.8$ kpc from the...
Sun, an estimated mass of $2 - 4 \times 10^4 M_\odot$, and an age of $7 - 12$ Myr (Figer et al. 2003). Stephenson 2 has 26 red supergiants, is located at $d = 5.8^{+1.9}_{-0.8}$ kpc from the Sun, has an estimated mass of $4 \times 10^4 M_\odot$, and an age of $12 - 17$ Myr (Davies et al. 2007). Their distances from the Sun are the same, within uncertainties, and their projected separation on the sky is $\approx 100$ pc. The designation Stephenson 2 was originally given by Ortolani et al. (2002), and also adopted by Dias et al. (2002, and updates). Stephenson 2 and BDSB 122 are clearly in the red supergiant (RSG) phase (Davies et al. 2007). Their distances from the Sun are the same, within uncertainties, and their projected separation (Davies et al. 2007). Their distances from the Sun are the same, within uncertainties, and their projected separation (Davies et al. 2007).

The positions (and uncertainties) of both clusters, together with $\omega$ Centauri (NGC 5139), are shown in Fig. 2 superimposed on a schematic view of the Milky Way (based on Momany et al. 2006 and Drimmel & Spergel 2001). The locus of BDSB 122 and Stephenson 2 is slightly more internal than the Scutum-Crux arm. Several other young clusters

from the catalogues of Bica et al. (2003) and Dutra et al. (2003) have already been studied in detail (e.g. Soares et al. 2008; Ortolani et al. 2008; Hanson & Bubnick 2008).

We trace backwards in time the orbits of $\omega$ Centauri and that of the OC Stephenson 2 (and consequently, also that of BDSB 122) in the disk, testing an impact hypothesis for the origin of these two massive OCs. Orbit integrations in the Galactic potential using as constraints the GC space velocity have been widely applied to 54 GCs (e.g. Dinescu et al. 2003; Allen, Moreno & Richarod 2008).

This paper is structured as follows. In Sect. 2 we study the past orbit of $\omega$ Centauri. In Sect. 2.1 the past orbits of Stephenson 2 and $\omega$ Centauri are compared looking for spatial and time coincidence. Conclusions are in Sect. 3.

### Table 1. Present-day cluster positions

| Cluster  | $\ell$ | $b$ | $\alpha(J2000)$ | $\delta(J2000)$ |
|----------|-------|-----|----------------|-----------------|
|          | ($^\circ$) | ($^\circ$) | (h:m:s) | ($^\circ$, $'^\prime$, $''$) |
| (1)      | (2)    | (3)  | (4)            | (5)             |
| $\omega$ Centauri | 309.10 | +14.97 | 13:26:46 | -47:28:37 |
| BDSB 122 | 26.84  | +0.65  | 18:37:58 | -6:53:00  |
| Stephenson 2 | 26.18  | -0.06  | 18:39:20 | -6:01:44  |

### 2. $\omega$ Centauri as a projectile

$\omega$ Centauri, the most massive Galactic GC ($4 \times 10^6 M_\odot$-Nakawa et al. 2001), has a metallicity spread and a flat density distribution typical of a dwarf galaxy nucleus captured by the Galaxy (Bekki & Freeman 2003). Thus, irrespective of the existence of young massive clusters, somehow associated with the impact site, the orbit of $\omega$ Centauri under the Galactic potential is worth studying, especially to look for consequences of the last disk passage. Evidence of a similar disk impact and a star-forming event has been observed in the spiral galaxy NGC 4559 with Hubble Space Telescope (HST), XMM-Newton, and ground-based (SCP05) data. The age of the star-forming complex is $\lesssim 30$ Myr, with a ring-like distribution. It appears to be an expanding wave of star formation, triggered by an initial density perturbation. The most likely triggering mechanism was a collision with a satellite dwarf galaxy crossing through the gas-rich outer disk of NGC 4559, which appears to be the dwarf galaxy visible a few arcsec NW of the complex. The picture is reminiscent of a scaled-down version of the Cartwheel galaxy (Struck-Marcell & Higdon 1993; Struck-Marcell et al. 1996).

As another example, proper motions (PMs) and radial velocity suggest that the GC NGC 6397 moved the Galactic disk 5 Myr ago, which possibly triggered the formation of the OC NGC 6231 (Rees & Cudworth 2003), thus lending support to the present scenario (Wallin, Higdon & Staveley-Smith 1996). NGC 6397 and NGC 6231 are closely projected on the sky ($\Delta \ell \approx 5^\circ$, $\Delta b \approx 13^\circ$). However, in the case of $\omega$ Centauri as possible generator of BDSB 122 and Stephenson 2, the GC is now widely apart from the pair of massive OCs ($\Delta \ell \approx 77^\circ$, $\Delta b \approx 15^\circ$). Thus, PM and radial velocity are fundamental constraints for the analysis of $\omega$ Centauri, and impact solutions require a detailed integration of the orbit across the Galactic potential.
Fig. 3. Top-left panel: Galactocentric XY-plane projection of the \( \omega \) Centauri orbit over the past 2 Gyr. Top-right: The past 30 Myr orbit of \( \omega \) Centauri (solid line) for \( R_{GC} = 7.2 \) kpc. Additional neighbouring orbits (dotted) are, from bottom to top: JHB96 (-10\%), JHB96 (+10\%), FSC96. The impact site on the disk is shown by the empty square. Arrows indicate orbit direction. Orbits of Stephenson 2 for the assumed distance from the Sun (and uncertainties) are shown. The corresponding XZ and YZ projections are in the bottom panels. Empty symbols over the Stephenson 2 orbits indicate its possible positions 24 Myr ago. The Sun at its present position (asterisk) and the Galactic Centre (filled circle) are shown.

2.1. Orbit computation

The present three-component mass-distribution model of the Galaxy follows that employed in the study of a high-velocity black hole on a Galactic-halo orbit in the solar neighbourhood (Mirabel et al. 2001, and references therein). In short, we use the three-component model of Johnston, Hernquist & Bolte (1996) – hereafter JHB96 – in which the disk, spheroidal, and halo gravitational potentials are described as \( \phi_{\text{disk}}(R, z) = -GM_{\text{disk}}/\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2} \) (Miyamoto & Nagai 1975), \( \phi_{\text{spher}}(R) = -GM_{\text{spher}}/R + c \) (Hernquist 1990), and \( \phi_{\text{halo}}(R) = v_{\text{halo}}^2 \ln(R^2 + d^2) \), where \( M_{\text{disk}} = 1 \times 10^{11} M_{\odot} \), \( M_{\text{spher}} = 3.4 \times 10^{10} M_{\odot} \), \( v_{\text{halo}} = 128 \) km s\(^{-1} \), \( R \) and \( z \) are the cylindrical coordinates, and the scale lengths \( a = 6.5 \) kpc, \( b = 0.26 \) kpc, \( c = 0.7 \) kpc, and \( d = 12.0 \) kpc. Table 1 shows the Galactic and Equatorial coordinates of the three clusters. Following Mizutani, Chiba & Sakamoto (2003), the relevant parameters for computing the motion of \( \omega \) Centauri are the distance from the Sun \( d_\odot = 5.3 \pm 0.5 \) kpc, the PM components (mas yr\(^{-1} \)) \( \mu_\alpha \cos(\delta) = -5.08 \pm 0.35 \) and \( \mu_\delta = -3.57 \pm 0.34 \), and finally the heliocentric radial velocity \( V_r = 232.5 \pm 0.7 \) km s\(^{-1} \).
The models were computed with $R_{GC} = 7.2$ kpc (Bica et al. 2006) as the distance of the Sun to the Galactic centre. The Galactic velocities of $\omega$ Centauri are $U = 54.3 \pm 9.5 \, \text{km s}^{-1}$, $V = -44.2 \pm 8.2 \, \text{km s}^{-1}$, and $W = -1.3 \pm 13.0 \, \text{km s}^{-1}$. Alternatively, we also computed orbits with $R_{GC} = 7.6$ kpc, obtained by Eisenhauer et al. (2005). It should be noted that recently, by means of statistical parallax of central stars, Trippe et al. (2008) found $R_{GC} = 8.07 \pm 0.32$ kpc, while Ghez et al. (2008), with the orbit of one star close to the black hole, found $R_{GC} = 8.0 \pm 0.6$ kpc or $R_{GC} = 8.4 \pm 0.4$ kpc, under different assumptions. Cluster distances are heliocentric, which do not depend on $R_{GC}$; on the other hand, the value of $R_{GC}$ has some effect on the potentials, which thus, affects orbit computation. Since the difference between the adopted value of $R_{GC}$ and the more recent ones is not exceeding, the value of $R_{GC}$ should not influence much the present results.

Based on the rotation curves of Brand & Blitz (1993) and Russell (2003), and an estimate with the galaxy mass model described above (Mirabel et al. 2001), we derived $V_c = 214 \pm 4 \, \text{km s}^{-1}$ as the orbital velocity of Stephenson 2. The nearly flat Galactic rotation curve at the Stephenson 2 position allows to adopt this circular velocity also for the orbits corresponding to distance uncertainties (Sect. 4). The orbit of $\omega$ Centauri, computed back over 2 Gyr, is comparable to that derived by Mizutani, Chiba & Sakamoto (2003) in particular the Rosette pattern seen projected on the XY plane (Fig. 3). The simulation shows that $\omega$ Centauri hit the disk as recently as $24 \pm 2$ Myr ago. Because of such a short time, fossil remains of this event may be detectable in the disk nowadays.

Figure 3 (top-left panel) shows the Galactic XY-plane projection of the last 2 Gyr orbital motion of $\omega$ Centauri. In the remaining panels we focus on the last 30 Myr of the motion of $\omega$ Centauri and Stephenson 2. For Stephenson 2 we consider the different orbits that result from the adopted distance from the Sun and corresponding uncertainties (Sect. 1). The interesting fact is that the orbit of Stephenson 2 passes close to the impact site of $\omega$ Centauri at a comparable time, within uncertainties (see below). Since Stephenson 2 and BDSB 122 have almost the same position (within uncertainties), the same conclusions hold for the latter cluster. The XZ and YZ-plane projections (bottom panels) show that $\omega$ Centauri emerged at $\approx 45^\circ$ from the plane to its present position.

To probe orbital uncertainties owing to the adopted potential, we also employed the potential model of Flynn, Sommer-Larsen & Christensen (1996) – hereafter FSC96 – and tested consequences of variations of $\pm 10\%$ in the input parameters of JHB96. The results are shown in Fig. 4 (top-right panel), from which we conclude that orbit variations due to the adopted potential are much smaller than our error ellipsoid (Fig. 4 right panel).

Close-ups of the $\omega$ Centauri impact site and the back-traced positions of Stephenson 2 are shown in Fig. 4 (left panel) for a Sun’s distance to the Galactic centre of 7.2 kpc and 7.6 kpc. It is clear that the latter value is not critical for the encounter. The right panel shows the error ellipsoid of several impact site simulations computed by varying initial conditions according to the errors in the different relevant input quantities. The ellipsoid reflects variations implied by velocity uncertainties in the PM, radial velocity and present position of $\omega$ Centauri along the line of sight in the (U,V,W) velocities. The impact obtained with a Galactocentric distance $R_{GC} = 7.6$ kpc is also shown. The disk-orbit of Stephenson 2 crosses the $\omega$ Centauri ellipsoid error distribution. The range in impact site to proto-cluster separations contains distances smaller than $\approx 1$ kpc, with an average separation of $\approx 500$ pc (intersection area in Fig. 4 right panel). Larger separations would require prohibitive expansion velocities, despite the fact that we are dealing with an encounter in a denser, central part of the disk, while in NGC 4559, the event was external.

Fig. 4. Close-up of the impact site. Left panel: Orbits computed with $R_{GC} = 7.2$ kpc (empty symbols) and $R_{GC} = 7.6$ kpc (filled symbols). Right: Same as left panel but including error distribution for the $\omega$ Centauri impact site and Stephenson 2 proto-cluster position. A random selection of impact sites (open circles) is shown within the $\omega$ Centauri error ellipsoid.
For the GC-induced formation hypothesis to be valid, the time-scales associated with the onset of star formation (after impact), duration of star formation and the cluster age, should be compatible with the disk-crossing age. Following [Putte & Cropper (2009)], the first time scale in not well known, ranging from virtually instantaneous, i.e. negligible as compared to the cluster age, to 15 Myr (Lépine & Duvert 1994) and 30 Myr (Wallin, Higdon & Staveley-Smith 1996). The star formation time-scale may be short, \( \approx 2 \times 10^4 \) yr, as suggested by McKee & Tan (2002) for stars more massive than 8 M\(_{\odot}\). Given that the ages of Stephenson 2 and BDSB 122 are their formation only if the star-formation onset occurred in less than \( \approx 15 \) Myr, which is within the accepted range. In the case of NGC 4559 these time-scales combined are less than \( \sim 30 \) Myr (Soria et al. 2003).

The above clues suggest an interesting event, that the most recent crossing of \( \omega \) Centauri through the disk occurred very close to the sites where two massive OCs were formed. Both Stephenson 2 and BDSB 122 are somewhat younger than the age of the impact, and the differences of a few Myrs are consistent with the shock propagation and subsequent star formation. The overall evidence gathered in the present analysis supports \( \omega \) Centauri as the origin of this localised star formation in the Galaxy, which harbours two of the more massive known OCs.

This work suggests a scenario where the disk passage of GCs can generate OCs, massive ones in particular, as indicated by the orbit of \( \omega \) Centauri and its impact site. As a consequence, not all OC formation is induced by the spiral density wave mechanism in spiral arms.

3. Summary and conclusions

Globular clusters orbiting the bulge and halo of the Galaxy cross the disk on average once every 1 Myr, and significant physical effects of such events on the disk are expected to occur. For instance, the impact of a GC passing through the disk can trigger star formation either by accumulation of gas clouds around the impact site or by the production of an expanding mechanical wave. Time delays are expected in both cases because of collapse and fragmentation of molecular clouds before star formation. This phenomenon has been recently observed in the galaxy NGC 4559 (e.g. SCP05). If this mechanism operates frequently in the Galaxy, the most massive GC \( \omega \) Centauri can be taken as an ideal projectile to prospect the state of its last impact site in the disk.

As \( \omega \) Centauri hit the Galactic disk \( \approx 24 \) Myr ago, a major star-forming event appears to have occurred close (\( \approx 1 \) kpc) to the locus that generated two of the most massive young OCs known in the Galaxy, BDSB 122 and Stephenson 2. We suggest the connection of these events in a way similar to the impact and shock wave observed in NGC 4559 (SCP05). We use a model of the Galactic potential to integrate the orbit of \( \omega \) Centauri. As shown in Fig. 4 when the uncertainties in space velocity, distances, and potential are considered, the error-distributions of \( \omega \) Centauri impact site and the birth-site of Stephenson 2 overlap. Such overlap suggests a scenario where the disk passage and formation of the pair of OCs may be physically connected. Alternatively, the time coincidence may have occurred within a separation \( \lesssim 1 \) kpc. In such case, the expanding bubble scenario such as that in NGC 4559 would apply. The latter case is more probable, since two clusters have been formed.

Levy (2000) performed 2D hydrodynamic simulations to study the impact of GCs on the Galactic disk in the presence of available gas. They found that the moving GC causes a shock wave in the gas that propagates through the disk in a kpc scale, thus producing star formation. More recently, Putte & Cropper (2009) simulated in detail the effects of GC impacts on the disk that basically confirm Wallin, Higdon & Staveley-Smith (1996) and Levy (2000), even in the absence of gas at the impact site. They found focussing of disk material with compression on a scale of \( \sim 10 \) pc, that may subsequently attract gas leading to star formation. The compression increases with the GC mass.

At this point an interesting question arises. For a rate of \( \sim 1 \) GC impact per Myr, it can be expected a high probability of occurring one GC impact within 1-2 kpc of any location within the inner Galaxy in about 10 Myr. However, the star-formation efficiency of these events appears to be low, according to Putte & Cropper (2009). Indeed, of the 54 GCs with accurate proper motions studied by them, only three appear to be associated to young OCs. Possibly, conditions like GC mass and impact site properties, such as the availability of molecular gas, temperature and density, constrain the star-formation efficiency.

Evidence drawn from the present work suggests that GCs can be progenitors of massive OCs. In particular we focused on \( \omega \) Centauri. Density-wave shocks are possibly the sole responsible for the formation of the more massive OCs, a possibility to be further explored, both theoretically and observationally.

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