Citation for published version:
J. Silk, V. Antonuccio-Delogu, Y. Dubois, V. Gaibler, M. R. Haas, S. Khochfar, and M. Krause, Letter to the Editor, 'Jet interactions with a giant molecular cloud in the Galactic centre and ejection of hypervelocity stars', *Astronomy & Astrophysics,* Vol. 545, L11, (2012).

DOI:
http://dx.doi.org/10.1051/0004-6361/201220049

Document Version:
This is the Published Version.

A&A 545, L11 (2012)
DOI: 10.1051/0004-6361/201220049

Astronomy & Astrophysics

Letter to the Editor

Jet interactions with a giant molecular cloud in the Galactic centre and ejection of hypervelocity stars

J. Silk[1,2,3], V. Antonuccio-Delogu[4], Y. Dubois[1], V. Gaibler[5], M. R. Haas[6], S. Khochfar[7], and M. Krause[8,7,9]

[1] Institut d'Astrophysique de Paris, CNRS, 98bis bd Arago, 75014 Paris, France
[2] Department of Physics and Astronomy, The Johns Hopkins University Homewood Campus, Baltimore, MD 21218, USA
[3] BIPAC, Department of Physics, University of Oxford, Oxford OX1 3RH, UK
e-mail: silk@astro.ox.ac.uk
[4] INAF – Osservatorio Astrofisico di Catania, via S. Sofia 78, Catania, & Scuola Superiore di Catania, via Valdisavoia 9, 95123 Catania, Italy
[5] Universität Heidelberg, Zentrum für Astronomie, Institut für Theoretische Astrophysik, Albert-Ueberle-Str. 2, 69120 Heidelberg, Germany
[6] STScI, 3700 San Martin Drive, Baltimore, MD 21218, USA
[7] Max-Planck Institut für extraterrestrische Physik, PO Box 1312, 85478 Garching, Germany
[8] Excellence Cluster Universe, Technische Universität München, Boltzmannstrasse 2, 85748 Garching, Germany
[9] Geneva Observatory, University of Geneva, 51 Chemin des Maillettes, 1290 Versoix, Switzerland

Received 18 July 2012 / Accepted 29 August 2012

ABSTRACT

The hypervelocity OB stars in the Milky Way Galaxy were ejected from the central regions some 10–100 million years ago. We argue that these stars, as well as many more abundant bound OB stars in the innermost few parsecs, were generated by the interactions of an AGN jet from the central black hole with a dense molecular cloud. Considerations of the associated energy and momentum injection have broader implications for the possible origin of the Fermi bubbles and for the enrichment of the intergalactic medium.

Key words. galaxies: active – stars: formation – Galaxy: center

1. Introduction

Hypervelocity stars (HVS) in our galaxy defy explanation. With velocities directed outward from the centre of the galaxy of between 300 and 1000 km s^{-1}, these young OB stars cannot be explained by ejection from binaries or via binary encounters with the central black hole.

Most hypervelocity stars seem to be the relics of something more exotic than binary ejections. The more massive the star, the higher the run-away fraction. Since a significant fraction are O stars of $\gtrsim$40 $M_{\odot}$, this means the event that generated them was relatively recent. Binary star scattering by a central star cluster fails by at least two orders of magnitude to account for their frequency (Perets & Subr 2012). Binary ejection in supernovae seems unlikely given that their orbits are consistent with coming from the nucleus of the Milky Way Galaxy (MWG) and the travel times of hypervelocity B supergiants, around 3–4 $M_{\odot}$, at 50–100 kpc from the Galactic centre (GC) and with velocities $\gtrsim$300 km s^{-1}, are constrained to 60–200 Myr (Brown et al. 2012).

More exotic possibilities have been investigated. The Milky Way's central supermassive black hole might itself have a companion black hole, which could kick off the stars at high speed (Yu & Tremaine 2003; Baumgardt et al. 2006; Sesana et al. 2008). The main difficulties with this scenario are that the velocities could come out to be too high (Sesana et al. 2008), and that if dynamical friction with the stars in the dense GC is taken into account, a continuous supply of intermediate mass black holes inspiralling into the GC must be invoked, because each one may only eject stars for a timescale of 10^6 yrs (Baumgardt et al. 2006). About 100 HVS (B stars of 3–10 $M_{\odot}$) are generated in the halo over a typical propagation time of 100 Myr, or at a mean ejection rate of 1/Myr ejected. We infer that the ejection most likely was spread over 10^6 to 10^8 yrs because of the spread in distances travelled and lifetime considerations.

Recurrent active galactic nucleus (AGN) activity is an established piece of galaxy evolution, in contrast to recurrent accretion of intermediate mass black holes. Hence if there is no other convincing explanation, it is useful to estimate whether the mechanism of origin of hypervelocity stars may be due to positive feedback on molecular gas induced by jet interactions generated by past explosions from our central supermassive black hole (SMBH).

AGN jets have recently been shown via 3-D simulations to overpressure clouds and induce star formation in gas-rich central disks (Gaibler et al. 2012). Another recent study of AGN jets interacting with an cloudy interstellar medium demonstrates that 10% or more of the jet energy effectively accelerates the gas clouds to escape velocity over a few tens of millions of years (Wagner et al. 2012). Neither of these studies includes cloud self-gravity, and one must await new studies before reaching any definitive conclusions, for example on cloud survival. However it is nevertheless useful to point out that there may be a local counterpart of jet-induced gas flows and induced star formation, for which the energetics and efficiencies seem to work out surprisingly well.

Our own central black hole currently has a very low accretion rate, but this may not have been the case in the past. Indeed, jet activity has recently been claimed from radio data (Yusef-Zadeh et al. 2012b). This leads the possibility that an eus (AGN)-like phenomenon may have repeatedly occurred in our own GC.

Indeed, the recently discovered Fermi bubbles in the central regions of the Galaxy may provide evidence for an outburst some 10 million years ago, provided reacceleration of energetic electrons occurred in the associated shocks (Su et al. 2010; Guo & Mathews 2012; Zubovas et al. 2011). Hypervelocity B stars suggest an event some 100 million years ago.

Our starting point is that of momentum considerations. There is an intriguing coincidence between the momentum flow from the GC and that in hypervelocity stars that connects, we believe, to an outstanding problem in galaxy formation theory. The point here is that production of HVS is inefficient. Most of the stars formed by jet-induced overpressuring of GC gas clumps are inevitably at relatively low velocity. These are tracers however of the same mechanism that generated the rarer HVS. Hence we first describe star formation in the inner few parsecs.

2. Star formation in the Galactic centre

The Milky Way Nuclear Star Cluster has a radius of 5 pc and a mass of 2–3 $\times$ 10^7 $M_\odot$ (Launhardt et al. 2002). It has several components, including the Sgr A* star cluster which contains ~200 young stars within the central parsec. There is also disk structure, with a main and an inclined disk at 0.8–12 arcsec (1 arcsec = 0.04 pc) of massive stars formed 6 Myr ago, as well as a more isotropic distribution of older (>1 Gyr old) stars containing 90% of the stellar mass within the central parsec (Pfuhl et al. 2011).

The IMF of the WR, O, B stars in the central disks (in the innermost 4000 AU, 0.8–12 arcsec) is top-heavy (Bartko et al. 2010). The WR and O stars formed coevally about 6 Myr ago. In addition there are late B (less massive) stars more isotropically distributed. Closer in there is an old star cluster with a standard IMF centred on Sgr A*. The B stars beyond 12 arcsec also have a standard IMF. There could be a correction for less massive stars, possibly as large as 10, in the central arc-sec. If the central OB stars (within 1 arcsec) were also formed by the jet interaction 10 Myr ago, the HVS ejection efficiency is inferred to be of order 1–10%.

Further out, the Arches cluster alone has a present day kinematic mass 1.5×10^4 $M_\odot$ (Clarkson et al. 2012). It is 26 pc from the GC and only 2 Myr old. The precursor molecular cloud mass of an Arches-like young massive star cluster is observed to be at a typical scale of 3 pc and mass of 10^5 $M_\odot$, see Longmore et al. (2012). In our model, the jet-driven bubble radius accelerates and compresses gas out to ~30 pc, where it can continue to induce star formation.

At 10% star formation efficiency (SFE), we would expect 10^5 $M_\odot$ in stars. In fact we see some 3×10^4 $M_\odot$ in low mass stars within 0.1 pc by using the integrated light at HST resolution of the central arc-second of the GC (Yusef-Zadeh et al. 2012a).

2.1. A giant molecular cloud around the central SMBH

At high redshift, the specific star formation rate (SFR) is observed to be high. This is due either to an increase in the efficiency of star formation related perhaps to the increase in gas supply or to a new mode of star formation. The former interpretation, if coupled to the metallicity dependence of molecular gas formation, fails to simultaneously fit low and high redshift specific star formation rates (Khochfar & Silk 2011; Krumholz & Dekel 2012).

The occurrence of a new mode is plausibly related to the rapid rise in AGN activity, that parallels star formation rate histories, by $z \sim 2$. AGN interactions with gas-rich disks can provide positive as well as negative feedback, with positive feedback naturally augmenting the specific star formation rate, as in Gaibler et al. (2012). The latter study shows how the pressure enhancements associated with a powerful jet can pressurise the gas-rich disk and thereby trigger and accelerate the star formation rate. One consequence is ejection of gas clumps. We argue here that simple considerations of the momentum transfer and energetics support the case that stars forming in the ejected gas clumps can account for the hypervelocity stars, if the last such jet episode occurred some ten million years ago at the GC, and followed other similar episodes with an appropriate duty cycle determined by replenishment of the gas reservoir.

Dense molecular gas is mapped at the GC. Some is infalling and some is undergoing tidal disruption, but a significant fraction ends up in a central circumnuclear gas disk at 1.5–4 pc from the GC (Liu et al. 2012). The mass of the inner giant molecular cloud (GMC) amounts to 10^{6-7} $M_\odot$. The residual gas mass depends on the star formation efficiency and on the assumed IMF. Gas replenishment will guarantee repeated episodes of AGN activity and star formation. If we assume that non-axisymmetric gravitational instabilities drive GMC formation and infall, the gas replenishment time is of order 3×10^7 yr. The inferred duty cycle for AGN activity and nuclear star formation is a few percent. For simplicity, we assume the cloud to be spherical, although the physical mechanisms at work are expected to similarly apply for a wide range of geometries.

2.2. The role of AGN in cloud disruption

Let us consider momentum flux balance for a cloud of mass $M_{\rm cloud}$ and internal velocity dispersion σ: $\mathrm{d}(M_{\rm cloud}\sigma)/\mathrm{d}t = \dot{M}_{\rm w} v_{\rm w}$ or $M_{\rm cloud} = f_{\rm E} f_{\rm g} L_{\rm E} t_{\rm dyn} (c\sigma)^{-1}$, where a geometrical factor $f_{\rm g} \sim 1$ allows for the jet inefficiency in driving a quasi-spherical bow shock, $L_{\rm E}$ is the Eddington luminosity, $f_{\rm E}$ is the Eddington ratio ($L_{\rm AGN}/L_{\rm E}$) and $v_{\rm w} \sim (0.1\text{–}0.3)c$ is the initial wind velocity for a wind of mass outflow rate $M_{\rm w}$. During the active phase of the AGN, we take $f_{\rm E} = 0.1 f_{\rm E,0.1}$ with $f_{\rm E,0.1} \sim 1$, and one can disrupt some 10^6 $M_\odot$. The bow shock radius $r_{\rm s}$ is set by $4\pi\rho_{\rm g} r_{\rm s}^2 v_{\rm inf}^2 = \dot{M}_{\rm w} v_{\rm w}$, or $r \approx 2\ {\rm pc} \left[f_{\rm E,0.1} f_{\rm g} M_{\rm BH,4} n_5^{-1} v_{\rm inf,50}^{-2} \right]^{1/2}$, where $v_{\rm inf} = 50\ {\rm km\,s^{-1}} v_{\rm inf,50}$, $n = 10^5 n_5\ {\rm cm^{-3}}$, and $M_{\rm BH} = 4 \times 10^6\ M_{\rm BH,4}\ M_\odot$.

This is a conservative estimate, since the increased area of the thermal blast wave means that the jet-induced ram pressure plus ambient medium shocked gas thermal pressure exceeds the jet input momentum by one or even two orders of magnitude: e.g. $f_{\rm g} \sim 100$ at $\sim 10^6$ yr, depending on jet evolution (Wagner et al. 2012). The swept-out radius is of order a few parsecs, comparable to the molecular cloud scale. We assume the cloud feeds the AGN (and forms stars) over an initial dynamical time, and so the cloud should be disrupted by the AGN over a time-scale $\propto r^4$, of order 10^6 yr. A more detailed jet-driven bubble model is described below.

2.3. Star formation triggering by AGN

BH feeding and triggered star formation occur simultaneously. There is overwhelming evidence that AGN are capable of quenching star formation. This is certainly likely to be the case for the GMC within a few parsecs of the central black hole. However there is also expected to be star formation within the self-gravitating accretion disk that directly feeds the SMBH via both fragmentation and triggering. We expect the triggered nuclear star formation rate to be regulated by the enhanced pressure

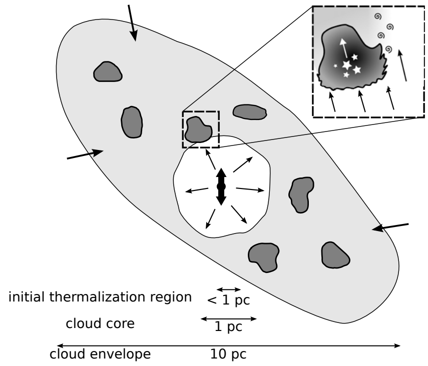

Fig. 1. Schematic model of jet/blast wave-cloud interaction in central 10 pc. The jet inflates a cocoon which punches into the GMC. The cloud is subjected to the wind arising from the systematic expansion of the cocoon, which has the dual effect of compressing its outer layers, thereby triggering star formation, and accelerating some the newly formed stars to become hypervelocity stars.

and to be proportional to the square root of the pressure (Silk & Norman 2009).

For a SFE of 0.02 per dynamical time in a $10^6\ M_\odot$ GMC, one forms $2\times10^4\ M_\odot$ of stars per dynamical time, 10^5 yr, or 20 times the nuclear star formation rate (SFR). The mass fraction of this GMC that forms stars over a cloud lifetime is of order ~1%. The high star formation rates observed near AGN motivate us to assert that the star mass fraction formed is elevated, to say ~10%. The enhanced SFR is justified if the pressure of the central cloud is elevated by a factor ~100 compared to nearby GMCs, as is the case if the cloud is self-gravitating and of size 10 pc and mean density $\sim10^{4-5}$ cm^{-3}.

A top-heavy IMF is motivated observationally for the star-forming disks at the GC (Bartko et al. 2010). If the cloud continues to form stars for ~10 cloud free-fall times, it forms some 20% of its mass in stars over its lifetime, or $2\times10^5\ M_\odot$ in stars. There are of order 10^4 OB stars for a top-heavy IMF.

3. The model

The simulations of the interaction of a jet with a gas-rich disk galaxy Gaibler et al. (2012) show that radio lobes develop and drive a quasispherical blast wave, as long as the jet length is smaller than the vertical scale height of the disk. The jet then escapes vertically and the sideways expansion of the blast wave stalls. HVS form in the shell at the sites of pre-existing overdensities, as long as the shell expands rapidly. After breakout, more stars form with smaller velocities.

This picture may also apply to the disky cloud around our galaxy's SMBH. In this case, the jet should have a total power L of a fraction of the Eddington luminosity of $L_{\rm E}=5\times10^{44}$ erg/s (for mass $4\times10^6\ M_\odot$). The jets will collimate and develop lobes from around the inner scale L_1 (e.g. Krause et al. 2012), given by $L_1\approx 0.01$ pc $(L/L_{\rm E})^{1/2}(\rho_0/10^5\,mp)^{-1/2}(v_{\rm j}/c)^{-3/2}$, where the central cloud density is ρ_0, and the jet velocity is $v_{\rm j}$.

Within a molecular cloud centred on the SMBH, a jet should develop lobes and bow shocks just as in the more familiar extragalactic radio sources, and the results of Gaibler et al. (2012) may be scaled down to the GC, due to the high density of molecular clouds. A sketch of our model is provided in Fig. 1.

The ejection efficiency is the central idea of our model. With 2% star formation efficiency (per dynamical time), and a cloud life-time of 10 dynamical times, regulated by AGN disruption, one could form a total of 10^4 stars each of mass $\sim20\ M_\odot$ (assuming a top-heavy IMF). For a more conventional IMF, one would form far fewer OB stars, perhaps only ~100, requiring a correspondingly higher ejection efficiency. We infer that ~1% of OB stars need to be ejected in the event. In this case, the total stellar mass ejected is $\sim2000\ M_\odot$ and the associated gas mass ejected is $4\times10^4\ M_\odot$, or a few percent of the GMC.

These numbers seem to work for the Milky Way Galaxy. Let us assume that in one of these events, 100 stars of average mass $10\ M_\odot$ are ejected at 300 km s^{-1}. Their total momentum flux is 6×10^{43} g cm/s. Over 10^6 yr, the momentum flux ejected is 2×10^{30} dynes. The SMBH at the GC has an Eddington luminosity of 5×10^{44} erg/s (for mass $4\times10^6\ M_\odot$) and we have assumed that it radiates at 10% of the Eddington rate. If the outflow were momentum-driven, the ratio of AGN radiative pressure $L_{\rm Edd}(4\pi r^2 c)^{-1}$ to mechanical wind pressure $\dot{M}v(4\pi r^2)^{-1}$ is $L_{\rm Edd}(\dot{M}vc)^{-1}=\eta c/v\sim10$, where v is the wind velocity and $\eta\sim0.1$ is the radiative efficiency of accretion. The associated momentum flux (for optical depth unity, $f=1$) is $fL_{\rm Edd}/c=1.7\times10^{34}f$dynes (actually observations require a factor $f\sim10$ to account for the $M_{\rm BH}-\sigma$ relation (Silk & Nusser 2010)). In this case, the ejection efficiency is $1.2\times10^{-4}/f$. This seems reasonable even for $f_{\rm E}\sim0.1$.

The momentum transfer is determined by the ram pressure of the jet-driven expanding blast wave. The increased surface area of the expanding bow shock results in a substantial boost in momentum-driving (Krause & Gaibler 2010), more quantitatively demonstrated in Wagner et al. (2012). Additional ways of enhancing the momentum transfer include an energy-driven blast wave (King 2003; Faucher-Giguere & Quataert 2012) and a non-isothermal dark halo (McQuillin & McLaughlin 2012). Similar enhancements are required to explain the observed outflows, as recently advocated in Sturm et al. (2011).

We estimate the ejection velocity of a gas clump by assuming that a jet with power $10^{44}\ L_{44}$ erg/s drives a blast wave into a cloud with initial density $10^5 n_5$ cm^{-3} and radius $5R_5$ pc (we ignore density stratification here). We emphasize that it is not actually the jet itself that accelerates clumps and induces star formation, but rather the associated cocoon/shock wave. Note also that the tidal radius is roughly $r_{\rm t}\sim r_{\rm c}(M_{\rm c}/M_{\rm BH})^{1/3}$ (e.g. (Murray-Clay & Loeb 2011). If the tidal radius is larger then the extent of the cloud, star formation is not affected by tidal forces, and self-gravitating cores are further stabilized.

The bubble radius evolves as $R_{\rm b}=(5L/(4\pi\rho_0))^{1/5}\,t^{3/5}$, and the cloud is eroded over a time $R_{\rm b}^{5/3}((4\pi/5)\rho/L)^{1/3}\sim5\times10^3\,R_5^{5/3}$ $(n_5/L_{44})^{1/3}$yr, shorter than the free fall time. While star formation in the whole cloud abruptly terminates, the diffuse gas of the cloud is compressed into a dense shell that cools on a very short timescale $t_{\rm c}\approx100T_7^{1/2}n_5^{-1}$ years, where 10^7T_7 K is the initial temperature of the shocked cloud gas. Any initial density inhomogeneities will then clump due to thin shell and gravitational instabilities (Vishniac 1983). At the edge of the cloud, the clumps should acquire a velocity of $v_b=600L_{44}^{1/3}n_5^{-1/3}R_5^{-2/3}$ km s^{-1}. The momentum of the shell when it reaches the edge of the cloud would be 10^{47} g cm/s, sufficient to explain the HVS observations, even if only a fraction of the gas forms stars. The time scale difference between acceleration and fragmentation is important: the cloud will in fact be disrupted, but stars are formed in the process.

These clumps should cruise at basically constant speed until they form stars, because due to clumping and density stratification the clumps are much denser than their surroundings. If we assume a ten to hundredfold increase of the density in the shell, compared to the average cloud density, we infer a free fall time of several 10^4 up to 10^5 yrs. Assuming an exterior density of 100 cm^{-3}, as observed in the hot gas today (Baganoff et al. 2003), the expanding shell would have to accelerate to several 1000 km s^{-1}. This triggers Rayleigh-Taylor instabilities, so that the clumps disconnect from the shell, which reforms at higher speed and continues to sweep away the interstellar medium. Even at the present epoch, the observed jet might lead to some HVS ejections, as direct jet-cloud interactions should lead to molecular cloud acceleration up to ≈270 km s^{-1} (Yusef-Zadeh et al. 2012b).

HVS formation might also manifest an anisotropic geometry. There is a suggestion that the hypervelocity stars are found in two thin disk planes (Lu et al. 2010). A disk-like geometry is indeed suggested by the numerical simulations of triggered star formation (Gaibler et al. 2012). Skewed jets are commonly observed (Kinney et al. 2000; Lagos et al. 2011), and it is hardly plausible that successive misaligned feeding disks would prefer the same plane of symmetry (Lodato & Pringle 2006).

Another manifestation of a recent AGN triggering episode may be the recently discovered Fermi gamma ray bubbles. The Fermi bubbles require $E_{\rm bubble} = 10^{55}$ erg or more in energy input into the relativistic plasma. The associated momentum is $E_{\rm bubble}/c = 3 \times 10^{44}$ g cm/s. Over 10^6 yr this amounts to a rate of 10^{31} dynes. It is also roughly equal to the momentum flux in the ejected stars for the usual SFE of 10% of that in the total gas plus stars ejected). This seems reasonable if most of the energy injected is thermal. In fact the required efficiency for driving the star-forming clumps is even smaller as the AGN wind model for the Fermi bubbles (Zubovas & Nayakshin 2012) requires $\sim 10^{57}$ erg injection in a few 10^5 yr and a jet power of $\sim 10^{44}$ erg/s.

4. Cosmological implications

One consequence of jet-induced clump acceleration leading to young star ejection is that jet-induced cloud/star motions could retain some orbital memory of a central as opposed to a disk injection mode. Another global consequence is that nuclear ejection would have happened more often in the past for our MWG, and much more vigorously in the past for galaxies with more massive BH than that of our MWG.

Some 100 10 $M_\odot$ stars ejected per 10^7 yrs imply 10^5 star ejections over the age of the MWG. Let us allow a factor of ~10 for past enhanced activity, that is some 10^6 stars or 10^7 $M_\odot$ are ejected from the MWG. These stars would become SNII in the intergalactic medium (IGM). The inferred mean metallicity generated is 10^{-4} solar (since a L_* galaxy of 10^{11} $M_\odot$ accounts for solar yields). This provides the observed IGM abundance floor. Moreover the IGM abundance floor (which is indeed about this value from Ly alpha forest data) should be α-enhanced. The stars would have travelled a distance (300–3000) km s^{-1} × 6 Myr or 1.8–18 kpc. Over 3×10^7 yrs, this amounts to 9–90 kpc. This results in IGM enrichment on halo and on group scales. This is about what might be expected, for an enrichment of the surrounding MWG IGM at $z = 0$, and will provide ubiquitous enrichment for the IGM at $z \sim 2$ when AGN activity peaks and distances are smaller.

Of course, the number of events depends on the gas refuelling rate. Since the gas accretion and SMBH fuelling rates were higher in the early MWG, one ejects even more stars. A rough estimate comes from scaling the SFR, which is fed by cold gas accretion and also scales with the BH accretion rate by a ratio of about 1000 (see Mullaney et al. 2012). The early SFR is enhanced by about a factor of 10 in order to account for disk chemical evolution, e.g. Cescutti et al. (2009). This gives a factor of approximately 10 boost in OB star ejection relative to a constant rate, with corresponding implications for the time-dependence of the chemical evolution of the IGM. The fact that the triggering mode is more efficient at high z suggests that any surviving high velocity stars from early episodes should be biased to lower metallicity.

A time delay of 50–100 Myr has been measured for several hypervelocity stars apparently ejected from the GC (Brown et al. 2012). These represent only a small fraction of the hypervelocity stars. Our model predicts that only ~1% of the newly formed jet-induced stars are ejected promptly. It is possible that a significant fraction of the newly formed massive stars may have massive binary companions, leading to a time delay of 4×10^7 yr or longer, if the binary companion exploded as a core collapse supernova or as a prompt SNIa single degenerate core (Maoz et al. 2012).

In summary, we have argued that many of the observed hypervelocity stars were generated by the interactions of an AGN jet-driven cocoon from the central black hole with a dense molecular cloud. There are broader implications for nuclear star formation, the enrichment of the IGM and the possible origin of the Fermi bubbles.

Acknowledgements. J.S. and Y.D. acknowledge support by the ERC project "Dark Matters", MK by the cluster of excellence "Origin and Structure of the Universe" (www.universe-cluster.de), and VG by the Sonderforschungsbereich SFB 881 ("The Milky Way System", subproject B4) of the German Research Foundation (DFG). We thank Zachary Dugan for discussions.

References

Baganoff, F. K., Maeda, Y., Morris, M., et al. 2003, ApJ, 591, 891
Bartko, H., Martins, F., Trippe, S., et al. 2010, ApJ, 708, 834
Baumgardt, H., Gualandris, A., & Portegies Zwart, S. 2006, MNRAS, 372, 174
Brown, W. R., Cohen, J. G., Geller, M. J., & Kenyon, S. J. 2012, ApJ, 754, L2
Cescutti, G., Matteucci, F., McWilliam, A., Chiappini, C., et al. 2009, A&A, 505, 605
Clarkson, W., Ghez, A., Morris, M., et al. 2012, ApJ, 751, 132
Faucher-Giguere, C.-A., & Quataert, E. 2012, MNRAS, 425, 605
Gaibler, V., Khochfar, S., Krause, M., & Silk, J. 2012, MNRAS, 425, 438
Guo, F., & Mathews, W. G. 2012, ApJ, 756, 181
Khochfar, S., & Silk, J. 2011, MNRAS, 410, L42
King, A. 2003, ApJ, 596, L27
Kinney, A. L., Schmitt, H. R., Clarke, C. J., et al. 2000, ApJ, 537, 152
Krause, M., Alexander, P., Riley, J., & Hopton, D. 2012, MNRAS, in press [arXiv:1206.1778]
Krause, M., & Gaibler, V. 2010, in AGN Feedback in Galaxy Formation, 18–22 May, 2008, Vulcano, Italy, eds. V. Antonuccio-Delogu, & J. Silk (CUP), 183
Krumholz, M. R., & Dekel, A. 2012, ApJ, 753, 16
Lagos, C. D. P., Padilla, N. D., Strauss, M. A., et al. 2011, MNRAS, 414, 2148
Launhardt, R., Zylka, R., & Mezger, P. G. 2002, A&A, 384, 112
Liu, H. B., Hsieh, P.-Y., Ho, P. T. P., et al. 2012 [arXiv:1207.6309]
Lodato, G., & Pringle, J. E. 2006, MNRAS, 368, 1196
Longmore, S. N., Rathborne, J., Bastian, N., et al. 2012, ApJ, 746, 117
Lu, Y., Zhang, F., & Yu, Q. 2010, ApJ, 709, 1356
Maoz, D., Mannucci, F., & Brandt, T. 2012 [arXiv:1206.0465]
McQuillin, R. C., & McLaughlin, D. E. 2012, MNRAS, 423, 2162
Mullaney, J. R., Daddi, E., Béthermin, M., et al. 2012, ApJ, 753, L30
Murray-Clay, R. A., & Loeb, A. 2011 [arXiv:1112.4822]
Netzer, H. 2009, ApJ, 695, 793
Perets, H. B., & Subr, L. 2012, ApJ, 751, 133
Pfuhl, O., Fritz, T. K., Zilka, M., et al. 2011, ApJ, 741, 108
Sesana, A., Haardt, F., & Madau, P. 2008, ApJ, 686, 432
Silk, J., & Norman, C. 2009, ApJ, 700, 262
Silk, J., & Nusser, A. 2010, ApJ, 725, 556
Sturm, E., González-Alfonso, E., Veilleux, S., et al. 2011, ApJ, 733, L16
Su, M., Slatyer, T. R., & Finkbeiner, D. P. 2010, ApJ, 724, 1044
Vishniac, E. T. 1983, ApJ, 274, 152
Wagner, A. Y., Bicknell, G. V., & Umemura, M. 2012, ApJ, 757, 136
Yu, Q., & Tremaine, S. 2003, ApJ, 599, 1129
Yusef-Zadeh, F., Bushouse, H., & Wardle, M. 2012a, ApJ, 744, 24
Yusef-Zadeh, F., Arendt, R., Bushouse, H., et al. 2012b, ApJL, in press [arXiv:1208.1193]
Zubovas, K., & Nayakshin, S. 2012, MNRAS, 424, 666
Zubovas, K., King, A. R., & Nayakshin, S. 2011, MNRAS, 415, L21