HIGH VELOCITY STAR FORMATION IN THE LMC

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ABSTRACT

Light-echo measurements show that SN1987A is 425 pc behind the LMC disk. It is continuing to move away from the disk at 18 km s$^{-1}$. Thus, it has been suggested that SN1987A was ejected from the LMC disk. However, SN1987A is a member of a star cluster, so this entire cluster would have to have been ejected from the disk. We show that the cluster was formed in the LMC disk, with a velocity perpendicular to the disk of about 50 km s$^{-1}$. Such high velocity formation of a star cluster is unusual, having no known counterpart in the Milky Way.

Magellanic Clouds, Supernovae: Individual (SN1987A)

1. INTRODUCTION

The Large Magellanic Cloud (LMC) shows a clear contrast between regular kinematics and irregular structure, with its offcenter bar and lack of any clear stellar spiral morphology. The velocities as traced by carbon star velocities (Graff et al. 2000; Hardy et al. 2000; Kunkel et al. 1997) and by H$\alpha$ emission (Kim et al. 1999) are well fit by a rotating disk although there may be a non-disk component (Graff et al. 2000; Luks & Rohlfs, 1992). The overall velocity dispersion of the carbon stars $\sim 20$ km s$^{-1}$ is small compared to the rotational velocity of the LMC $(60 - 70$ km s$^{-1}$) indicating that the stellar component of the LMC is relatively flat and rotationally supported. Moreover, Graff et al. (2000) showed that the younger, metal rich carbon stars in the inner $4^\circ$ of the LMC have a much lower velocity dispersion, only 8 km s$^{-1}$. This contrast suggests that the LMC lies in a nearly face-on plane, but is irregular within that plane.

The three-dimensional structure of LMC dust was measured using the “light-echo” technique on SN1987A by Xu, Crotts & Kunkel (1996). They identified 12 separate dust sheets. Most significantly, in this work and in a follow up spectroscopic study (Xu & Crotts 1999), they identified three components with the spherical shell N157C enclosing the OB association LH 90. This shell was found to lie 490 pc in front of SN1987A. Including the LMC inclination of $\sim 30^\circ$, the component of this distance perpendicular to the LMC plane is 425 pc.

This distance is much greater than the virial thickness of the young stellar population of the LMC in the location of SN1987A $\sim 90$ pc (given the local surface density of 100 $M_\odot$/pc$^2$ which we determine below). Thus, it is difficult to imagine how these two young stellar populations came to be so separated. Xu et al. (1996) suggest that SN1987A is a “...runaway star behind the disk of the Large Magellanic Cloud”.

Classical runaway stars can be found high above the Milky Way plane (Conlon et al. 1990). The runaway O and B stars are thought to be ejected by one of two processes: supernova explosions in close binary systems (Blaauw 1961) and strong dynamical interactions in star clusters (Poveda, Ruiz, & Allen 1967; Gies & Bolton 1986). Indeed, Hipparcos measurements of O and B stars have found several runaways that can be identified as having been ejected from particular OB associations (de Zeeuw et al. 1999).

However, Eremov (1991) and Panagia et al. (2000) have identified SN1987A as belonging to KMK 80 (Kontizas, Metaxa & Kontizas 1988) “...a loose young cluster 12 ± 2 Myr old...” (Panagia et al. 2000). Thus, it cannot be a classic runaway star; any of the violent ejection mechanisms discussed above would eject only the single star, and not its cluster.

In the next section, we solve for the initial kinematics of SN1987A and its associated cluster, KMK 80. We find that the cluster formed in the LMC plane, moving with a velocity of 50 km s$^{-1}$ perpendicular to the LMC plane.

2. KINEMATICS OF SN1987A

We begin by examining the velocities of these two young clusters relative to the LMC. The disk solution of Hardy et al. (2000) at the projected position of SN1987A is $271 \pm 1$ km s$^{-1}$.

By comparison, SN1987A has a redshift of 286 km s$^{-1}$ (Meaburn, Bryce & Holloway 1995) while the N157C complex containing LH 90 has a redshift of 270 km s$^{-1}$ (Xu & Crotts 1999). Thus, the velocity of LH 90 is perfectly consistent with the LMC disk velocity at this point.

On the other hand, SN1987A is in two respects inconsistent with being a member of the cold population: first, it is moving 15 km s$^{-1}$ relative to the disk, faster than the 8 km s$^{-1}$ typical of the cold population. Secondly, and more importantly, it lies far above the scale height of the cool population (and even above the scale height of the hot population).

To take account of both effects simultaneously, we define the “vertical energy” of a star to be $E \equiv v_z^2/2 + \Phi(z)$ and approximate the potential energy to be $\Phi(z) \approx 2\pi G \Sigma |z|$ for stars of height $z \gg 150$ pc. An examination of the isophotal map of the LMC of de Vaucouleurs (1957) shows that the surface brightness of the LMC in the neighborhood of SN1987A is about 21.7 mag./arcsec$^2$, or 56 $L_\odot$ pc$^{-2}$. Assigning a Population I mass-luminosity ratio of 1.7, we derive a mass surface density of roughly $\Sigma_{SN1987A} \approx 100 M_\odot$ pc$^{-2}$. We derive a total energy of
1300 (km s\(^{-1}\))^2 corresponding to a midplane velocity of 50 km s\(^{-1}\). Thus, the total gravitational energy of the supernova is much too high for it to be a member of the cold population (and somewhat high even for the hot population).

We note that the age of the star cluster containing the supernova is about 12 Myr which is consistent with estimates of the age of the precursor to the supernova. If the star cluster was formed at the LMC plane 12 Myr ago, with a velocity perpendicular to the plane of 50 km s\(^{-1}\), and this velocity decreased with a gravitational acceleration of \(-3 \text{ km s}^{-1} \text{Myr}^{-1}\), it would today be \(\sim 400\) pc above the plane moving at 14 km s\(^{-1}\), consistent with its measured distance of 425 pc above the plane and relative velocity of 15 kms.

3. DISCUSSION

The match between these numbers is compelling, and we suggest that the entire KMK 80 star cluster was formed 12 Myr ago at the LMC plane, but with an extraordinarily high velocity of 50 km s\(^{-1}\) perpendicular to the plane. The agreement between age and flight time is typical of most runaway O and B stars in the halo of the Milky Way (Keenan, Brown & Lennon 1986).

We do not know what mechanism could create a star cluster moving at such high velocities. As far as we know, there is no counterpart in the Milky Way. However, we can speculate on two possible mechanisms. First, the cluster might have formed as part of a galactic fountain pushed out of the LMC by supernovae or stellar winds. Such a mechanism was put forward by Xu & Crotts who suggested that SN1987A was formed on a shelf of gas pushed out of the LMC by LH 90. These authors noted that SN1987A is on the outskirts of the extremely violent 30 Dor. region.

Second, a dense cloud of gas could have smashed through the LMC disk, triggering star formation in the process with the resulting stars carrying some of the initial momentum of the cloud. This cloud could have been fountain material raining back down onto the LMC disk, or it could have been a high velocity cloud orbiting either the LMC or the Milky Way.

There are a few systems in the Milky Way that might have been formed in processes similar to the KMK 80 cluster. In addition to runaway O stars, the Milky Way Halo also contains young, high velocity, high metallicities A stars (Perry 1969; Rodgers 1971). These stars are all roughly the same age, \(< 650\) Myr (Lance 1988), which suggests that they were created from the collision of a Magellanic Cloud sized galaxy with the Milky Way disk (Rodgers, Harding, & Sadler 1981; Lance 1988). A similar recent collision in the LMC might generate high velocity star formation without breaking up KMK 80.

Gould’s belt (Gould 1974; Pöppel 1997) contains several OB associations in a roughly planar region oriented 18° from the plane of the Milky Way. Comerón & Torra (1994) suggested that Gould’s belt arose from the glancing collision of a high velocity cloud with the Milky Way disk. Perhaps KMK 80 is part of a similar structure oriented more nearly perpendicular to the LMC plane.

Logically, there are only two alternatives to our interpretation that KMK 80 formed at high vertical velocity. First, KMK 80 may actually lie in the LMC plane while the progenitor of SN1987A is simply seen projected against this cluster, having been earlier ejected from a binary. This appears to us to be a priori unlikely and can in any event be tested by spectroscopic observations of KMK 80 members. In addition to confirming SN1987A as a radial-velocity member of this cluster, such measurements would yield the metallicity of the cluster and so of the SN1987A progenitor.

Second, SN1987A could actually lie in the LMC plane while N157C lies 490 pc closer to us. Then, either LH 90 would still be at the center of N157C, or it would lie in the LMC plane and be seen by chance projected against the center of this cloud. In the first case, one would still have the same problem of an OB association lying far from the LMC plane. As for the second case, the probability of a chance projection of two such naturally associated structures seems incredibly low. In either case, KMK 80 would have to have been born with a vertical energy at least equal to its present kinetical energy of \((15 \text{ km s}^{-1})^2\), which is still quite high. Moreover, the N157C cloud would have to have exactly the same radial velocity as the LMC plane despite the fact that it lies \(~ 400\) pc from it. Hence, the various alternatives to our interpretation, while not actually ruled out, require extraordinary combinations of coincidences.

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REFERENCES

Blaauw, A. 1961, Bull. Astron. Inst. Netherlands, 15, 265
Comerón, F., & torra, J. 1994, ApJ, 423, 652
Conlon, E.S., Dufton, P.L., Keenan, F.P., & Leonard, P.J.T. 1990, A&A, 236, 357
Efremov, Yu.N. 1991, PAZh, 17, 404 (in Russian, translated into English in 1991, Sov. Astr. Lett., 17, 173)
Gies, D.R., & Bolton, C.T. 1986, ApJS, 61, 419
Graff, D.S., Gould, A.P., Schommer, R., Suntzeff, N. & Hardy, E. 2000, ApJ submitted (astro-ph/0001476)
Gould, B.A. 1874, Proc. AAAS, 115
Hardy, E., Schommer, R.A. & Suntzeff, N.B. 2000, in preparation
Keenan, F.P., Brown, P.J.F., & Leonardo, J.D. 1986 A&A, 155, 333
Kim, S. et al. 1998, ApJ, 503, 674
Kontizas, E., Metaxa, M. & Kontizas, M. 1988, AJ, 96, 1625
Kunkel, B.E., Demers, S., Irwin, M.J., Loic, A. 1997, ApJ, 488, 129
Lance, C.M. 1988, ApJ, 334, 927
Luks, Th., & Rohils, K. 1992, A&A, 263, 41
Meaburn, J., Bryce, M. & Holloway, A.J. 1995, A&A, 299, 1
Panagia, N., Romaniello, M, Scuderi, S & Kirshner, R.P. 2000, ApJ in press (astro-ph/0001476)
Perry, C.L. 1969, A.J., 74, 199
Pöppel, W.G.L. 1997, Fund. Cosmic Phys., 18, 1
Poveda, A., Ruiz, J., & Allen, C. 1967, Bol. Obs. Tonantzintla y Tacubaya, 4, 860
Rodgers, A.W. 1971, ApJ, 165, 581
Rodgers, A.W., Harding, P., & Sadler, E. 1981, ApJ, 244, 912
de Vaucouleurs, G. 1957, A.J., 62, 69
Xu, J. & Crotts, A.P.S. 1999, ApJ, 511, 262
Xu, J., Crotts, A.P.S. & Kunkel, W.E. 1996, ApJ, 463, 391
de Zeeuw, P.T., Hoogerwerf, R., de Bruijne, J.H.J., Brown, A.G.A., & Blaauw, A. 1999, AJ, 117, 354

Luks, Th., & Rohils, K. 1992, A&A, 263, 41
Meaburn, J., Bryce, M. & Holloway, A.J. 1995, A&A, 299, 1
Panagia, N., Scuderi, S & Kirshner, R.P. 2000, ApJ in press (astro-ph/0001476)
Perry, C.L. 1969, A.J., 74, 199
Pöppel, W.G.L. 1997, Fund. Cosmic Phys., 18, 1
Poveda, A., Ruiz, J., & Allen, C. 1967, Bol. Obs. Tonantzintla y Tacubaya, 4, 860
Rodgers, A.W. 1971, ApJ, 165, 581
Rodgers, A.W., Harding, P., & Sadler, E. 1981, ApJ, 244, 912
de Vaucouleurs, G. 1957, A.J., 62, 69
Xu, J. & Crotts, A.P.S. 1999, ApJ, 511, 262
Xu, J., Crotts, A.P.S. & Kunkel, W.E. 1996, ApJ, 463, 391
de Zeeuw, P.T., Hoogerwerf, R., de Bruijne, J.H.J., Brown, A.G.A., & Blaauw, A. 1999, AJ, 117, 354