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THE ORIGIN OF THE LOCAL BUBBLE[1]

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ABSTRACT

The Sun is located in a low-density region of the interstellar medium partially filled with hot gas that is the likely result of several nearby supernova explosions within the last 10 Myr. Here we use astrometric data to show that part of the Scorpius-Centaurus OB association was located closer to the present position of the Sun 5–7 Myr ago than today. Evolutionary synthesis models indicate that the association must have experienced ∼20 supernova explosions in the last 10–12 Myr, a prediction that is supported by the detection of four or five runaway stars escaping from it. The approximately six supernovae produced by the Lower Centaurus Crux subgroup are likely responsible for the creation of the Local Bubble.

Subject headings: ISM: bubbles — ISM: structure — open clusters and associations: individual (Scorpius-Centaurus Association) — solar neighborhood — stars: distances — supernovae: individual (Scorpius-Centaurus Association)

1. INTRODUCTION

The low-density region of the local interstellar medium (ISM) where the Sun is located is called the local cavity and is partially filled with hot ($\sim10^6$ K) low number density (~0.005 cm^{-3}) coronal gas detectable in soft X-rays (Sfeir et al. 1999; Snowden et al. 1998). The hot component of the local cavity is the Local Bubble (LB) and is likely to have been produced by a series of several supernova (SN) explosions within the last 10 million years (Smith & Cox 2001 and references therein). Since the number density of early-type stars in the immediate solar neighborhood is very small (Maíz-Apellániz 2001), it appears unlikely that several nearby isolated massive stars would have exploded within such a short time period (Smith & Cox 2001). Furthermore, no OB associations of the right age exist within 100 pc of the Sun at this time, so the identity of the SN progenitors that produced the LB has remained hidden until now. The search for the culprits was severely hampered until recently by the impossibility of accurately tracing the past positions of the stars in the solar neighborhood, but the advent of the data produced by the ESA *Hipparcos* astrometry satellite (ESA 1997) has changed the situation.

The local cavity has an approximate linear size of 200 pc and is slightly more elongated along the axis parallel to the Galactic rotation than along the radial axis, with fingers extending toward Galactic longitude $l = 310°$ and maybe also toward $l = 240°$. It is also more extended toward the north Galactic pole (NGP) than toward the south Galactic pole, being probably open-ended in the first direction (Sfeir et al. 1999). It has been mapped using different techniques, such as Na I and H I absorption (Sfeir et al. 1999; Vergely et al. 2001), dust extinction and polarization (Franco 1990; Leroy 1993), and the distribution of EUV sources (Welsh et al. 1994). The extension of the LB itself is more difficult to measure since it is easily detected only in soft X-rays (Snowden et al. 1998; Sanders et al. 1998) and EUV broadband data (Lieu et al. 1993), where confusion with other diffuse sources complicates the interpretation of measurements, and in O VI absorption, where data toward only a few directions are available (Shelton & Cox 1994). The nondetection of emission lines in the EUV (Jelinsky, Vallerga, & Edelstein 1995; Vallerga & Slavin 1998) suggests that a depleted or nonequilibrium 10^6 K plasma is the dominant component of the LB (Smith & Cox 2001). The local cavity is surrounded by denser gas that is moving slowly (Magnani, Hartmann, & Speck 1996) and, therefore, can be used to a first-order approximation as a fixed reference system.

2. PRESENT AND PAST POSITIONS OF THE SCO-CEN OB ASSOCIATION

The local cavity is not only poor in gas but also in hot stars. Only three O–B5 stars are found within 67 pc of the Sun, and none of them are earlier than B2 (Maíz-Apellániz 2001). Recently, de Zeeuw et al. (1999) have analyzed the census of the OB associations within 650 pc of the Sun position. The Scorpius-Centaurus OB association (Sco-Cen) is the nearest one and can be divided into three subgroups (Blaauw 1964): Lower Centaurus Crux (LCC), Upper Centaurus Lupus (UCL), and Upper Scorpius (US). In Table 1, we show their ages as measured by de Geus, de Zeeuw, & Lub (1989). In the left panel of Figure 1, we show the present position of the center of each subgroup (de Zeeuw et al. 1999), and in the right panel of Figure 1 we show a blowup with the position of the OB stars with well-determined distances in each subgroup using the procedure established by Maíz-Apellániz (2001). In order to analyze whether some of the former members of Sco-Cen that must have already exploded as SNe may have contributed to the creation of the LB, we used the membership lists and the data presented by de Zeeuw et al. (1999) to calculate the positions of the center of each subgroup in the past. We used a coordinate system that is centered at the present Sun position, moves with the Galaxy at its local rotation speed (i.e., it is a local standard of rest), and has x, y, and z defined by the direction of Galactic rotation, the outer radial direction, and the NGP, respectively. Velocities of the center of the subgroups have to be corrected for the effects of solar motion (Dehnen & Binney 1998) and Galactic rotation (Feast & Whitelock 1997). The motion of a star in the z-direction can be described as a harmonic oscillation with a period of 83 Myr and centered

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TABLE 1
Observed and Expected Number of OB Stars and SNe in Each Subgroup

Subgroup	Age (Myr)	Measured Number O–B2.5	Measured Number B3–B9.5	Measured Number SNe	Expected Number O–B2.5	Expected Number B3–B9.5	Expected Number SNe
LCC ……	11–12	5–7	31–35	≥2	7	32	6
UCL ……	14–15	14–17	44–49	≥2	10	52	13
US ……..	5–6	12–15	30–36	≥1	11	36	1

Note.—The ages were obtained from de Geus et al. 1989, and the measured numbers from de Zeeuw et al. 1999 and Hoogerwerf et al. 2001. The ranges given for the measured star numbers arise from uncertainties in the membership lists and spectral classification, while the measured numbers of SNe are the lower limits given by the known runaway stars. The expected numbers were obtained using Starburst 99 models (Leitherer et al. 1999) with solar metallicity, a Salpeter IMF, and an upper mass limit of 100 $M_\odot$. The expected number of previous SNe was calculated from the total number of OB stars and the age.

TABLE 2
Present and Past Positions of the Three Subgroups in Sco-Cen

Subgroup	*t* (Myr ago)	*x* (pc)	*y* (pc)	*z* (pc)
LCC ……	0	−100	−62	10
	5	−28	−59	3
	10	43	−79	−8
UCL ……	0	−67	−119	31
	5	6	−98	15
	10	82	−102	−7
US ……..	0	−20	−134	52
	5	31	−115	45

Note.—The positions refer to the center of each subgroup and use the coordinate system defined in the text. No position is given for US 10 Myr ago because the subgroup did not exist at that time.

at the Galactic plane (King 1996; Holmberg & Flynn 2000). The motion in the (*x*, *y*)-plane has a more complicated trajectory, but it can be approximately described by a retrograde ellipse with a period of 167 Myr and an axis ratio of 1.48, so that the motion of a star from a nonrotating point of view high above the Galaxy resembles an epicycle (King 1996; Feast & Whitelock 1997). Taking into account those effects, we have computed the positions of the three subgroups 5 Myr ago and the positions of UCL and LCC 10 Myr ago (US did not exist at that time). The results are shown in Table 2 and plotted in the left panel of Figure 1. We also show in Figure 1 the position of the Ophiuchus molecular cloud, as deduced from CO and *IRAS* data (de Geus et al. 1989; Loren 1989a, 1989b).

3. THE NUMBER OF SUPERNOVA EXPLOSIONS

It is clear from the left panel of Figure 1 that the Sco-Cen OB association (especially the LCC subgroup) was closer to the present Sun position ~5 Myr ago than today, which makes it a likely source for the approximately three SNe believed to be needed to produce the LB. As a first step to test this hypothesis, we need to verify how many SNe have been produced in Sco-Cen within the last 10 Myr. In order to do that, we counted the number of present O–B2.5 and B3–B9.5 stars in each subgroup using the membership lists of de Zeeuw et al. (1999) and the spectral classifications of the *Hipparcos* (ESA 1997) and Michigan (Houk & Swift 1999) catalogs (Table 1). Main-sequence O–B2.5 stars are the ones that end up their lives exploding as SNe, since a B2.5 V star has a mass of ≈9 $M_\odot$. We compared the observed numbers of early/late OB stars with those predicted by Starburst 99 models (Leitherer et al. 1999) for stellar groups of the ages given in Table 1 with solar metallicity, a Salpeter initial mass function (IMF), and an upper mass limit of 100 $M_\odot$, and obtained the number of expected previous SNe. The first SN is expected to take place when the stellar group is 3–5 Myr old,[3] and then the rest of the SNe take place at an approximately constant rate during the next ~30 Myr. The results are also shown in Table 1.

The proportions of early-to-late OB stars in LCC and US

[3] The exact moment depends on the mass of the most massive star, which for relatively low-mass subgroups such as those in Sco-Cen is quite uncertain due to the stochastic nature of the star formation process.

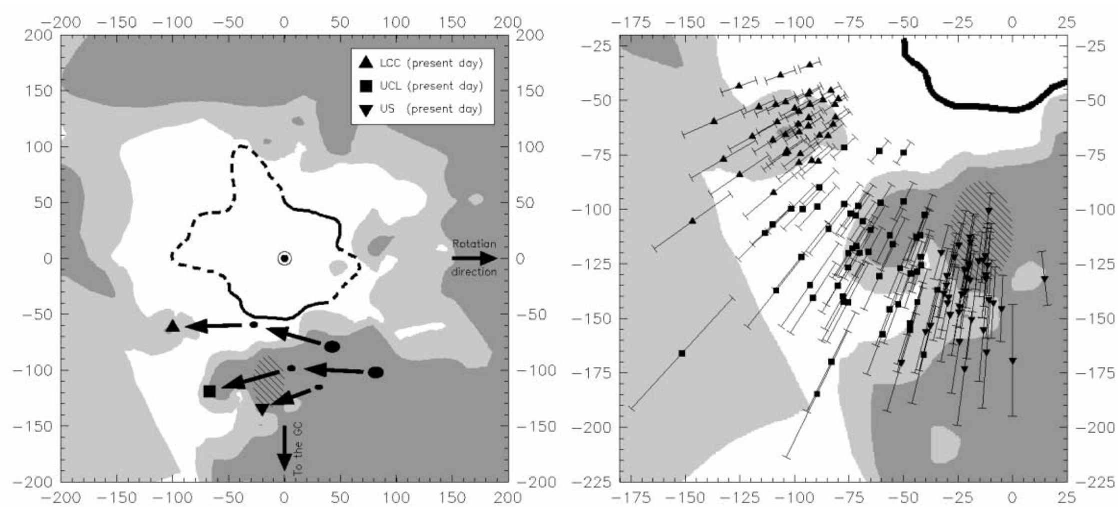

Fig. 1.—*Left*: Local cavity and LB in the plane of the Galactic equator. The filled contours show the Na i distribution (Sfeir et al. 1999), with white used for low-density regions and dark gray for high-density ones. The black contour shows the present size of the LB as determined from X-ray data (Snowden et al. 1998), with the dashed lines indicating contaminated areas where the limits of the LB cannot be accurately determined. The hatched ellipse shows the approximate position of the Ophiuchus molecular cloud (de Geus et al. 1989; Loren 1989a, 1989b). The present and past *x*- and *y*-coordinates of the center of the three subgroups of the Sco-Cen association are shown. For LCC and UCL, the past positions shown are those of 5 and 10 Myr ago, while for US only the position of 5 Myr ago is shown. The dimensions of the filled ellipses indicate the uncertainties in the past positions. Coordinates are expressed in units of parsecs. *Right*: Blowup of the left panel with the present positions of the OB stars in each of the three subgroups. Only those stars with accurately determined positions are shown. The symbol used in each case indicates the subgroup membership using the code established in the left panel.

are well fitted by the Starburst 99 predictions, so the expected number of SNe for those subgroups is probably quite reliable. The predictions are also in agreement with our knowledge of the US subgroup, where one SN took place 1 Myr ago (Hoogerwerf, de Bruijne, & de Zeeuw 2001), giving birth to the pulsar PSR J1932+1059 and ejecting the runaway star ζ Oph, and a red supergiant, Antares, is due to explode within the next few hundred thousand years. The proportion of OB stars in UCL is less well fitted by the model, probably indicating an anomalous IMF at upper masses (a phenomenon that is not at all surprising, since the small expected number of O–B2.5 stars can easily lead to stochastic fluctuations). However, even if we take the conservative approach of considering only half of the predicted SNe in UCL, there should still be approximately six SNe there exploding within the last 10–12 Myr plus another approximately six SNe in LCC in the last 7–9 Myr. These minimum values are supported by the detection of three or four additional runaway B1–B5 stars that appear to have been ejected (two from LCC and one or two from UCL) as a result of the explosion of their companions as SNe (Hoogerwerf et al. 2001). The LCC runaways were ejected 2.5 and 4.0 Myr ago, the certain UCL runaway 8.0 Myr ago, and the possible UCL runaway 3.0 Myr ago.

4. THE HISTORY OF THE LOCAL BUBBLE

Since there are so many predicted Sco-Cen SNe in the last 10–12 Myr, the question maybe should be not whether that association is responsible for the LB but rather why is not the bubble larger and approximately centered at its position of ~5 Myr ago (i.e., its weighted mean position within its SN-producing lifetime). A likely explanation is provided by Frisch (1998): the Ophiuchus molecular cloud (the remnant of the progenitor of Sco-Cen) and the larger Aquila Rift are located toward the first Galactic quadrant and would have impeded the expansion of the bubble toward $+x$ and $-y$ (at least close to the Galactic plane). On the other hand, the expansion toward $+y$ would have been facilitated by the existence of an interarm region there. We should also consider that the Ophiuchus molecular cloud probably shares its general motion with Sco-Cen (this cannot be proved with the data currently available since its proper motion is unknown but its radial velocity [Loren 1989b] is consistent with this statement). We would then expect that the motion of the molecular cloud in the negative x-direction would have made it occupy now part of the space previously held by the coronal gas, thus helping to create the partial Na I ridge between the LB and the Loop I superbubble, which appears in Figure 1 as the minimum around (-75, -150); note that the density contours there are probably not very precise.

The picture that emerges from the data in this Letter can then be summarized as follows. The LCC and UCL subgroups have produced enough SNe to create both the Local Bubble and the Loop I superbubble. Given their past positions, the two bubbles likely started as a single entity, with the SNe in LCC being primarily responsible for the expansion toward $+y$ (the current LB) and the SNe in UCL for the expansion toward $-x$ (the current Loop I superbubble). The approximately six LCC SNe would have exploded within a ~40 pc wide band of the trajectory of its center shown in the left panel of Figure 1, thus creating the LB part of the original Local Bubble–Loop I superbubble. Since LCC is currently abandoning the local cavity and any recent SN would have exploded quite far from its center, we would expect the dense material around it to have started to fill it up again (Smith & Cox 2001). That is what Figure 1 suggests, since the current extent of the LB just grazes the past trajectory of LCC.[4] If the LB appears to be in the last stages of its evolution, the forecast for the Loop I superbubble is more optimistic. Not only is most of UCL still inside it, but LCC is moving toward it and so is the younger subgroup US. All together, they are expected to produce ~35 SNe within the next 25–30 Myr, so its short-term survival seems to be more likely than that of the LB. Indeed, a recent SN explosion took place there and its remnant is expanding toward us at this time (Egger & Aschenbach 1995).[5]

Therefore, we can conclude that LCC was at the right place, at the right time, and experienced enough SNe to produce the LB. No other nearby OB association can be traced back in time to be in such a situation according to the data presented by de Zeeuw et al. (1999). Other authors (Frisch 1981; Breitschwerdt et al. 1996) have considered the possibility that the LB was created by Sco-Cen as a bubble expanding from its present position (i.e., as a blister of the Loop I superbubble). However, we have seen here that there is no need for such an explanation: most of the LCC SNe exploded much closer to the present position of the Sun, and the original bubble may have been larger than its present size since the motion of the Ophiuchus molecular cloud is probably closing the connection between the LB and the Loop I superbubble. The largest uncertainties in this picture lie in the extent of the original molecular cloud and in its current three-dimensional motion; the latter question could be answered when the Atacama Large Millimeter Array (Brown 2000) is built. Finally, we also have to mention that it cannot be excluded that a single (or even two) SN from the diffuse disk population may have contributed to the formation of the LB. However, as estimated by Smith & Cox (2001), the chances of having several of them exploding in our vicinity within a few megayears are rather low.

5. IMPLICATIONS

Apart from the relevance of the present study to the knowledge of the solar neighborhood, we would like to point out its implications with respect to the overall porosity of the ISM. Two competing theories suggest that the general morphology of the ISM is that of a “bubble bath” (McKee & Ostriker 1977; with hot bubbles occupying most of the available volume) or that of “Swiss cheese” (Slavin & Cox 1993; with hot bubbles occupying a smaller fraction of the volume). The fact that our Local Bubble can be traced back to a known OB association indirectly supports the Swiss cheese model, since it shows that approximately six SNe were unable to create a much larger bubble.

Another consequence of this study is that the proximity of the Sco-Cen association has increased by a significant factor the rate of SN explosions within 150 pc of the Sun in the last 6 Myr with respect to the mean rate in the last ~100 million years.[6] In a follow-up paper (Benítez, Maíz-Apellániz, & Canelles 2001), we explore the possible geological and biological consequences of those nearby SNe.

[4] Note, however, that one or two of the LCC SNe could have actually exploded within the present extent of the LB due to the finite extent of the subgroup.

[5] Those authors propose that the partial Na I ridge between the LB and the Loop I superbubble is the result of the interaction between the two of them produced by the most recent SNe.

[6] Note, however, that the increase is not as large as what could be deduced from a first look at the left panel of Fig. 1 because the Sun is moving from the upper left quadrant there.

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