Astron. Astrophys. 352, 308–316 (1999)

ASTRONOMY
AND
ASTROPHYSICS

EUV mapping of the local interstellar medium: the Local Chimney revealed?

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Received 30 August 1999 / Accepted 29 September 1999

Abstract. We discuss the galactic distribution of 450 sources detected by the EUVE satellite that have reliable distance estimates. Late-type stars dominate the nearby EUV source distribution, whereas the majority of EUV source detections with distances $>$ 100pc are hot white dwarf stars. The galactic distribution of all these sources is non-uniform with number enhancements seen towards the Hyades cluster, in line-of-sight along the β CMa interstellar tunnel and towards high galactic latitudes in both hemispheres. A comparison of the distribution of these EUV sources with that of the neutral absorption boundary of the Local Bubble region derived from the interstellar NaI observations of Sfeir et al. (1999) reveals that vast majority of EUV sources are contained within this neutral boundary. However, at high galactic latitudes 20 extragalactic EUV sources have been detected along lines-of-sight with low neutral column density, and is consistent with the local interstellar cavity being "open-ended" in the galactic halo. This "Local Chimney" opens towards two regions of enhanced intensity of the 0.25 keV soft X-ray background emission at high galactic latitudes. Although the hot Local Bubble gas is still contained within a cold, neutral interstellar gas boundary in the galactic plane, it has probably expanded into the halo to produce the Local Chimney feature.

Key words: ISM: atoms, ions – ISM: clouds – Galaxy: solar neighbourhood

1. Introduction

The NASA Extreme Ultraviolet Explorer (EUVE) satellite mission was launched in June 1992 and to date has detected over 1100 sources emitting EUV radiation in the 70 to 760 Å region (Lampton et al. 1997, Bowyer et al. 1996). The ability to detect celestial EUV sources is highly dependent on the amount of intervening line-of-sight neutral interstellar hydrogen gas, which is a very efficient absorber at these short wavelengths. Fortunately, the local interstellar medium (LISM), defined here as the volume surrounding the Sun to distances of $<$ 250 pc, is a region of unusually low neutral interstellar gas density ($n < 0.1\ cm^{-3}$) thus allowing appreciable numbers of nearby EUV sources to be detected. The essentially neutral gas-free cavity of the LISM is believed to be mainly filled with a rarefied million degree K hot gas (commonly called the Local Bubble, hereafter LB) that is thought to be the source of the ubiquitous soft X-ray background emission (Snowden et al. 1998).

Over the last decade there has been an increased focus in the study of the LISM in order to obtain detailed information on the physical properties and galactic distribution of the constituent LISM gas and to determine the past history of the LB region (see reviews by Frisch 1995, Breitschwerdt et al. 1998). In particular, Sfeir et al. (1999) have recently completed the first stage of a long-term program of mapping the galactic distribution of neutral interstellar NaI absorption within 300 pc of the Sun. These observations (which were based on measurement of interstellar NaI absorption taken over some 456 lines-of-sight) have revealed an absorption boundary (or "wall") of cold ($T < 1000$ K) neutral gas surrounding the hot LB. These maps clearly reveal the LB to be a highly asymmetric neutral gas-free interstellar cavity with radii varying between 65 to 250 pc, that is presumably filled with very low density, highly ionized million degree K gas. The outer boundary to the neutral gas wall of the LB region is defined by Sfeir et al. to possess a neutral hydrogen column density, N(HI), $> 5.0 \times 10^{19}\ cm^{-2}$, thus providing an appreciable optical depth to both EUV and soft X-ray photons. Hence, adopting the crude approximation that all EUV sources emit with same absolute spectral intensity, then the galactic distribution of known EUV sources should mostly lie within the Sfeir et al. neutral LB boundary. We note that Diamond et al. (1995) have found consistency between the observed galactic distribution of a sample of 79 EUV sources detected by the ROSAT EUV Wide-Field Camera and a simple model with a LB mean radius of 70 pc surrounded by a wall of neutral gas with N(HI) $< 10^{20}\ cm^{-2}$ within 100 pc in most galactic directions.

Although the majority of EUV sources (detected by both the EUVE and ROSAT Wide-Field Camera) are of local (galactic) origin, surprisingly some 20 active galaxies (Seyferts, BL Lac objects and quasars) were detected by EUVE in its very shortest wavelength band (60–175 Å) by Fruscione et al. (1996). The detection of these extragalactic EUV sources suggests that the LB wall neutral gas density must be considerably lower in directions away from the galactic plane when compared with mid-plane directions. Additionally, the ROSAT soft X-ray background emission maps of Snowden et al. (1997) show a marked enhancement towards both galactic poles, which is indicative of a reduction in the attenuation by the intervening neutral interstellar gas at high galactic latitudes. If the LB is typical of other galactic superbubbles (such as in Cygnus and the Gum Nebula) that are thought to have been formed by a combination of the stellar winds and supernova explosions of clustered OB stars, then it is probable that the LB cavity has expanded away from the galactic plane into the halo region. In such a scenario the hot, ionized LB gas is advected from the disk into the halo via the galactic fountain and chimney models (Edgar & Chevalier 1986, Shapiro & Benjamin 1991). In such a scenario we could expect the Local Bubble to be an open-ended interstellar tube-like structure with no appreciably dense, neutral gas boundary at high galactic latitudes.

Radio surveys of the 21 cm line of neutral HI indicate that at negative latitudes there are no regions with N(HI) < 0.8 x 10^{20} cm^{-2}, and at positive galactic latitudes this column density lower limit is $\sim 50\%$ smaller, particularly in the region towards the Lockman Hole in Ursa Major (Stark et al. 1992, Jahoda et al. 1990). In addition, it is believed that the lower halo region (z $>$ 250 pc) is occupied by a neutral layer of HI gas that lies just above the galactic plane with a column density of N(HI) $\sim$ 3 x 10^{19} cm^{-2} out to a distance of 1kpc (Lockman & Gehman 1991). Thus the radio observations, in concert with the EUV and soft X-ray data, suggest that there is no appreciably dense neutral wall to the LB at high galactic latitudes.

In this paper we present maps of the galactic distribution of 450 sources with reliable distance estimates detected by the EUVE satellite to investigate their relation to the neutral absorption boundaries of the LB region. We compare the EUV source distribution with the detailed absorption boundary contours of the Local Bubble region derived from NaI observations by Sfeir et al. (1999). By comparing these two source distributions together with the lines-of-sight towards EUV extra-galactic objects, we show that it is highly unlikely that the LB has a dense neutral boundary at galactic latitudes $> 50\,^{\circ}$. Thus, we now believe that the LB may well be an open-ended interstellar structure and is infact better described by the term “Local Chimney”.

2. Observational data

In order to accurately plot the galactic distribution of known EUV sources we have selected only those targets possessing both reliable stellar identification and reliable distance estimates. This represents a sub-set of 450 of the 1153 sources detected by the EUVE satellite that have been listed in the following three papers: (i) the EUVE all-sky scanner survey and deep ecliptic survey (Bowyer et al. 1996), (ii) the EUVE all-sky catalog of faint EUV sources (Lampton et al. 1997) and (iii) EUV sources detected during the EUVE right-angle program (RAP) for data taken with both the EUVE Deep Survey telescope and the all-sky scanner telescopes (Christian et al. 1999). The distance estimates for theses sources have been taken from: (i) for 333 late-type and 2 early-type stars we have used distances from the on-line Hipparcos catalog (ESA 1997) and (ii) for the case of 115 EUV emitting hot white dwarf stars we have used distances derived by Vennes et al. 1996 and Vennes et al.

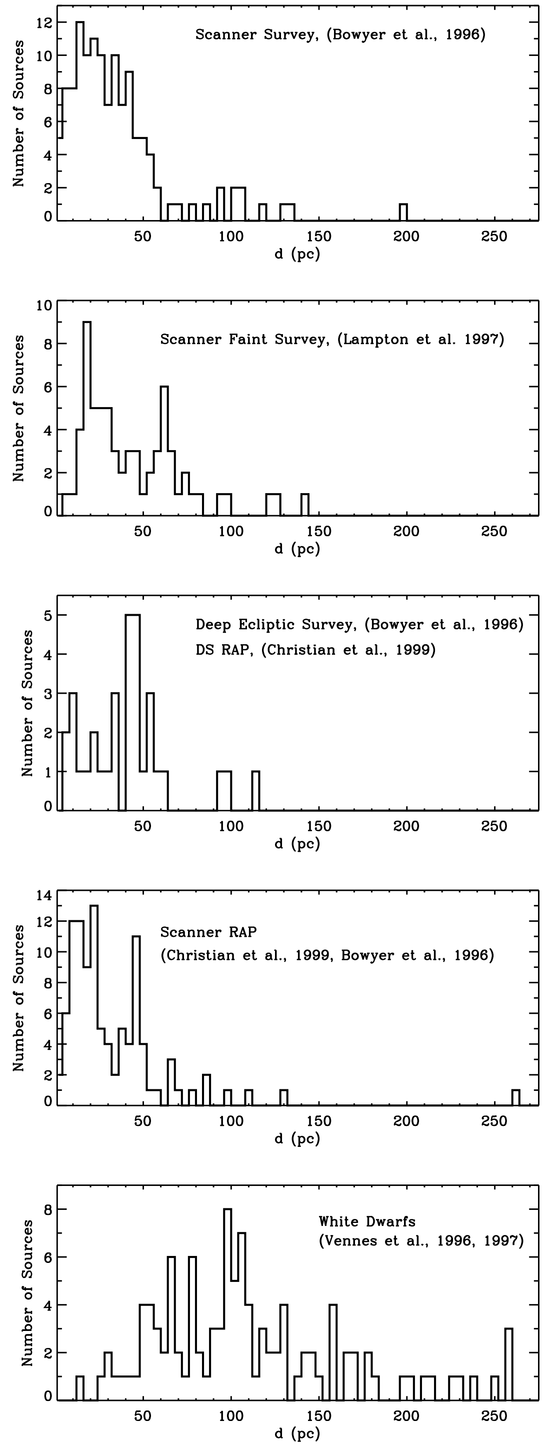

Fig. 1a–e. Histogram plots of the sources and their respective distances for each of the five EUVE data sets used in this paper.

1997. Hipparcos distance errors are typically $<$ 20% for stars within 500 pc, while the errors for hot white star distances (derived from theoretical modelling) are typically $\sim$ 25%. Note that we have omittted all early-type OB stars from our source list apart from the two B stars ϵ and β CMa which are both known to possess EUV spectral flux (Cassinelli et al. 1996). All other OB star “detections” by the EUVE satellite are assumed to be

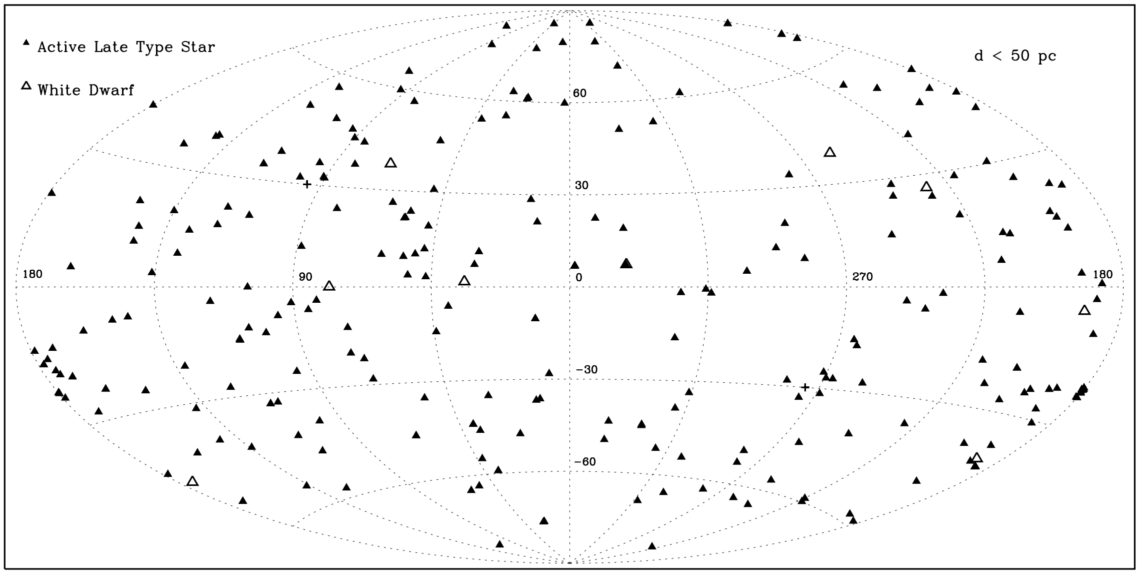

Fig. 2. Galactic distribution of sources detected by EUVE with known distances < 50 pc.

Table 1. EUVE source statistics

Catalog Name	N(tot)	N(Hip)	M	K	G	F	A	OB	Ref.
Scanner Survey	514	132	18	35	49	23	5	2	(1)
Scanner Faint Survey	183	64	6	12	18	24	4	0	(2)
Deep Ecliptic Survey + DS RAP	82	33	3	5	5	16	4	0	(1),(3)
Scanner RAP	374	106	17	24	33	28	4	0	(1),(3)
Source Totals	1153	335	44	76	105	91	17	2	

References: (1) Bowyer et al. (1996); (2) Lampton et al. (1997); (3) Christian et al. (1999).

caused by known far ultraviolet leaks in the EUV filters (McDonald et al. 1994). We also note that $\sim 40\%$ of EUVE source detections have (as yet) no corresponding stellar identification and thus have not been considered in this paper.

In Table 1 we show a number breakdown ordered by spectral type for each of the sources that were observed by the four EUVE sky surveys that have been used in our present paper. Only 335 of these EUV sources possess reliable Hipparcos catalog distance estimates, and hence our present sampling is biased towards visually bright, nearby stars mainly of spectral type F to M. Note that none of the 115 hot white dwarf stars appear in the Hipparcos catalog due to their faint visual magnitude.

In Fig. 1a–e we show histogram plots of the sources and their respective distances for each of the five EUVE data sets used in this paper (i.e. all-sky scanner survey, all-sky faint survey, Deep Ecliptic Survey + DS RAP observations, scanner telescope RAP observations and the EUV emitting hot white dwarfs contained in both the Vennes et al. papers). Inspection of these plots shows that the vast majority ($\sim 60\%$) of the EUVE source detections are nearby objects with distances < 50 pc. The majority of these nearby detections are active late-type stars which are known to have a high space density and are generally at the flux detection threshold of the EUVE instrument. However, we should note that 71 late-type stars were detected at distances > 50 pc by EUVE. The distance distribution of hot white dwarfs is clearly far more extended, with some sources having been detected to distances in excess of 250 pc. Infact, of all the EUVE sources detected with distances > 50 pc, hot white dwarfs represent 59% of the total.

2.1. EUV sources with distances < 50 pc

In Fig. 2 we show the galactic distribution of sources detected by EUVE with known distances < 50 pc, remembering that the vast majority of these sources are active late type stars of spectral type F to M. Inspection of this figure shows an inhomogeneous distribution of detections with several sky segments (such as the region bounded by galactic longitudes $145° < l <$ +180° and latitudes $> 60°$) showing no EUV sources with distances $<$ 50 pc. In order to quantify this EUV source distribution further, in Fig. 3 we show histogram plots of the number of detected sources (d $<$ 50 pc) as a function of galactic longitude binned for 4 ranges of galactic latitude. The most significant feature in the EUV source distribution is the three-fold increase in detections for the longitude range 150° to 210° for galactic latitudes -30° $< b < 0°$. This increase is in part due to the presence of active late-type stars associated with the nearby Hyades cluster (d = 44 pc), but this alone cannot explain the majority of the sources detected in this direction (the Hyades contribution is denoted by sources above the dotted line in Fig. 3). Although an increase in EUV source detections for this direction has been noted previously by Lampton et al. (1997), it was incorrectly attributed to the very low neutral interstellar column density direction towards the stars β and ϵ CMa (Welsh 1991), which in fact lies towards l = 235°, b = -15°. In addition we confirm the slight increase in source counts noted by Lampton et al. (1997) towards the directions l = 95° , b = +30° (due to EUVE's higher exposure levels at the ecliptic poles) and towards l = 180°, b = +45°(the line-of-sight to the star 36 Lynx which has a known low neutral interstellar column density).

Fig. 2 is also consistent with a slight deficit of source detections in the general direction surrounding the Galactic Center that has been noted previously (Frisch 1995, Pye et al. 1995), and has been attributed to a nearby (d $<$ 20 pc) absorbing cloud of neutral gas. However, ultraviolet and EUV absorption measurements towards stars within 30 pc indicate that that the neutral column density of N(HI) is $< 3.0 \times 10^{18}$ cm^{-2} in all directions (Dring et al. 1997, Lallement & Ferlet 1997 and Marsh et al. 1997), which is inconsistent with the level of absorption required to match the observed deficit in EUV source numbers in this direction. Inspection of the absorption cross-sections at 100 Å (the peak emission wavelength of active late-type stars) listed in Morrison & McCammon (1983) indicates that the most likely source of EUV opacity would be from a nearby (d $<$ 20 pc) photo-ionized interstellar cloud with an enhanced neutral HeI to HI ratio.

2.2. *EUV sources with distances > 100 pc*

In Fig. 4 we plot the distribution by spectral type of all detected EUV sources with distances $>$ 100 pc. It is immediately clear that the source distribution is far from uniform. There is a distinct lack of detections at mid-plane galactic latitudes that is consistent with the paucity of sources towards the Galactic Center region discussed previously, and an enhanced number of sources detected in both hemispheres at high galactic latitudes. This EUV source enhancement has been noted previously by Lampton et al. (1997) and is identified with an extended low HI column density region surrounding the general direction of the Lockman Hole centered on $l \sim$ 160° , $b \sim$ +55°.

We also note that although hot white dwarf stars dominate the EUV detections for distances $>$ 100 pc, there seems to be no differentiation in their galactic distribution with that of the (albeit) few detected late-type stars having similarly large distances. The EUV source distribution shown in this figure can be simply explained by assuming that a (dense) LB neutral absorbing wall of interstellar gas lies within 100 pc in most directions close to the galactic plane, whereas away from the mid-plane the neutral LB boundary (if one exists at all towards the galactic poles) is of far lower neutral gas density. We will further address the question of whether an LB neutral boundary actually exists at high galactic latitudes in Sect. 3.

Finally, we also note that EUV emitting cataclysmic variable stars (CVs) follow the same pattern of galactic distribution as the aforementioned hot white dwarf and AGN lines-of-sight, indicating that they have distances $>$ 100 pc. However, we have decided not to plot these data since CV distances are highly uncertain (Barrett et al. 1999).

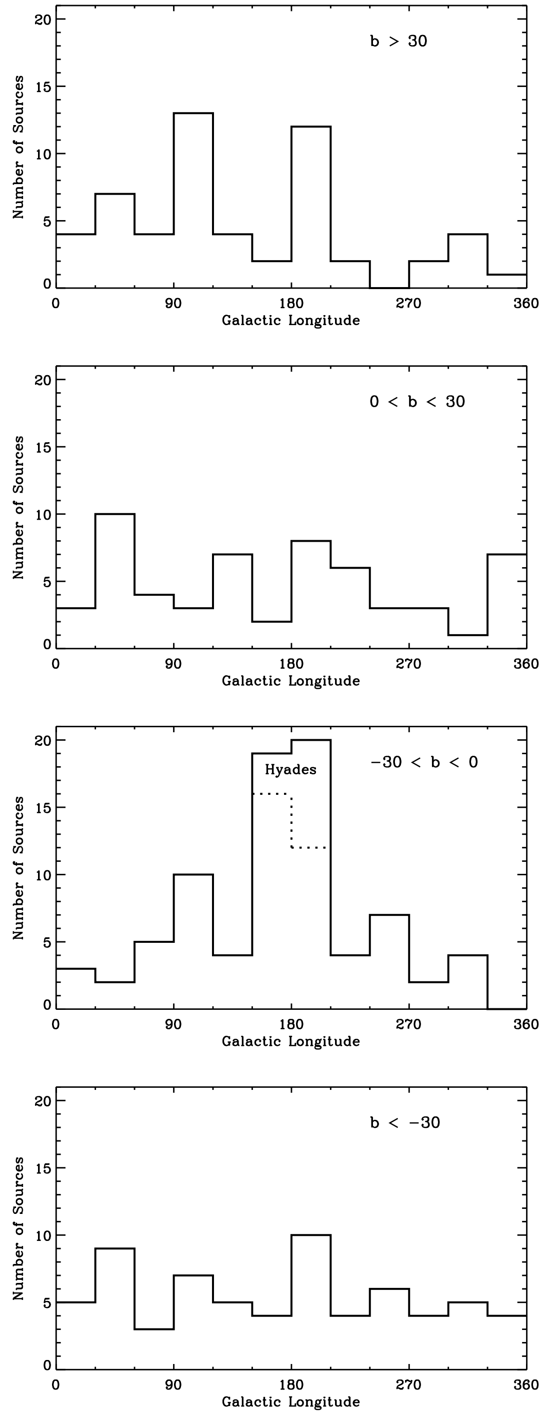

Fig. 3a–e. Histogram plots of the number of detected sources (d $<$ 50 pc) as a function of galactic longitude binned for 4 ranges of galactic latitude.

3. Comparison with NaI absorption maps

In order to test the simple explanations of the observed EUV source distributions given in Sect. 2, we have plotted the EUV

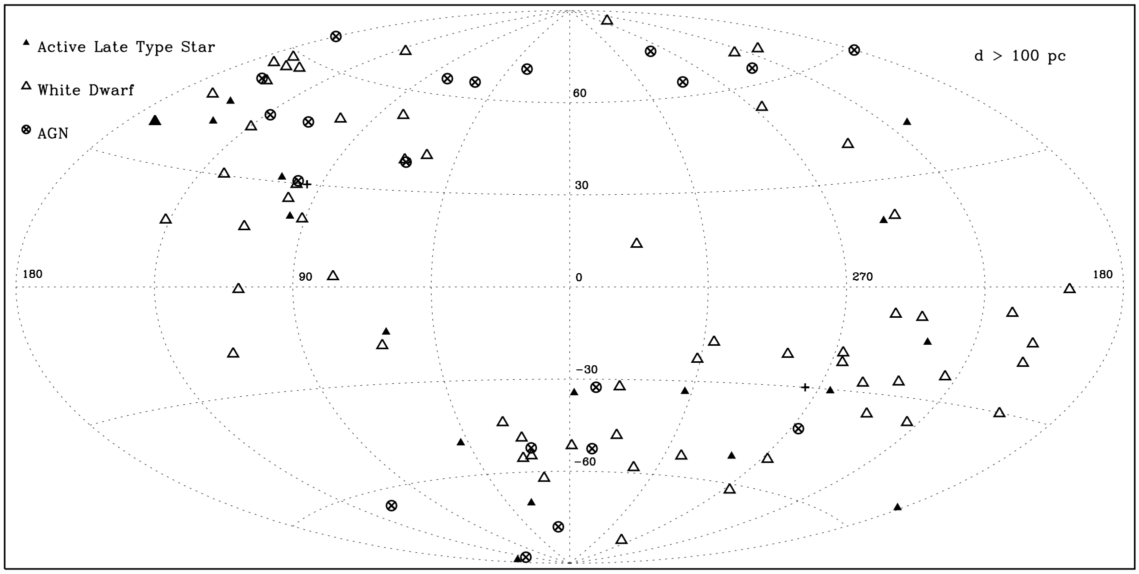

Fig. 4. Distribution by spectral type of all detected EUV sources with distances > 100 pc.

data on galactic maps that also show the neutral absorbing contours of the LB wall recently derived by Sfeir et al. (1999). This absorbing boundary (shown as thick solid lines in Fig. 5, Fig. 6, and Fig. 7) represents an equivalent width of NaI interstellar D2-line absorption of > 50 mÅ , which corresponds to a neutral hydrogen column density, N(HI), of > 5 x 10^{19} cm^{-2}. Regions of the LB boundary that are depicted by dashed lines in these figures correspond to lines-of-sight that have not been sampled beyond the nominal LB boundary by NaI observations, and thus the LB absorption contour in these directions is uncertain. Following the example of Sfeir et al. we present maps of the EUV source distributions as a function of distance viewed from 3 different galactic projections for the galactic, meridian and rotational planes.

In Fig. 5 we show the galactic distribution of EUV sources with distances < 300 pc contained within a swath of $\pm 18°$along the galactic plane as viewed from above the plane. The Sfeir et al. derived LB neutral boundary lies at a distance > 50 pc in all directions, whereas the majority of EUV source detections are < 50 pc and thus they should mostly lie within the LB neutral contour, as confirmed by Fig. 5. However, we also see that for the (albeit fewer) more distant EUV sources only 2 lie beyond the nominal LB boundary, both of which are in lines-of-sight not well defined by the nominal Sfeir et al. neutral boundary. For the case of the hot white dwarf star 0620+134 we note that due to its faint visual magnitude (V = 15.1) the error on its nominal distance of 183 pc may be as large as 30% which would place it just within the nominal LB contour (Dupuis, private communication). The other EUV detection beyond the nominal LB wall is the hot white dwarf star 0427+741, whose derived distance of 257 pc would appear inconsistent with our present results. Thus, although the EUVE source detections certainly do not constrain the neutral LB contours well in the galactic mid-plane, we note that their distance distribution does not conflict with the nominal Sfeir et al. LB neutral boundary.

In Fig. 6 we show the distribution of EUV sources as viewed perpendicular to the galactic plane that contains both galactic poles and the Galactic Center. Since this meridian projection extends into the galactic halo towards both poles, we have added all 20 of the extragalactic objects detected by EUVE as listed in Fruscione (1996). We have shown the direction of these extragalactic sources in Fig. 6 with arrows. Although the Sfeir et al. LB contours are undefined at high galactic latitudes for distances > 200 pc (due to a lack of suitable targets for NaI observations), the data suggests that the LB is most probably "open-ended" towards the halo in both hemispheres. We note that the sight-lines towards all but one of the EUV extragalactic sources shown in Fig. 6 are consistent with an open-ended LB with no appreciably dense, absorbing neutral boundary to the LB at high galactic latitudes. The validity of the Sfeir et al. contour is also confirmed by the fact that all but 2 of the galactic EUV sources are also contained within the LB neutral boundary. We note that the 2 exceptions are the hot white dwarfs 0620+134 (mentioned previously) and 0443-037 (d = 144 pc), both of which would be consistent with the LB boundary if their derived distances were $\sim 30\%$ less than those derived by Vennes et al..

In Fig. 7 we show the distribution of EUV sources as viewed perpendicular to both views of Fig. 5 and Fig. 6 that contains both galactic poles and is perpendicular to the Galactic Center direction. This map shows a large widening of the LB towards the North Galactic Pole, whereas it narrows considerably in the halo region towards the South Galactic Pole. Again we note that the LB boundary contour is consistent with the majority of extragalactic EUV source sight-lines and all but 2 of the galactic EUV source lines-of-sight. The notable extragalactic source exception is the Seyfert galaxy 1ES 0425-573, whose sight-line (l = 266° , b = -42°) is in a region of excess EUV source detections (see Fig. 4), and could well be serendipitously located along a narrow, low column density line-of-sight that extends into the halo.

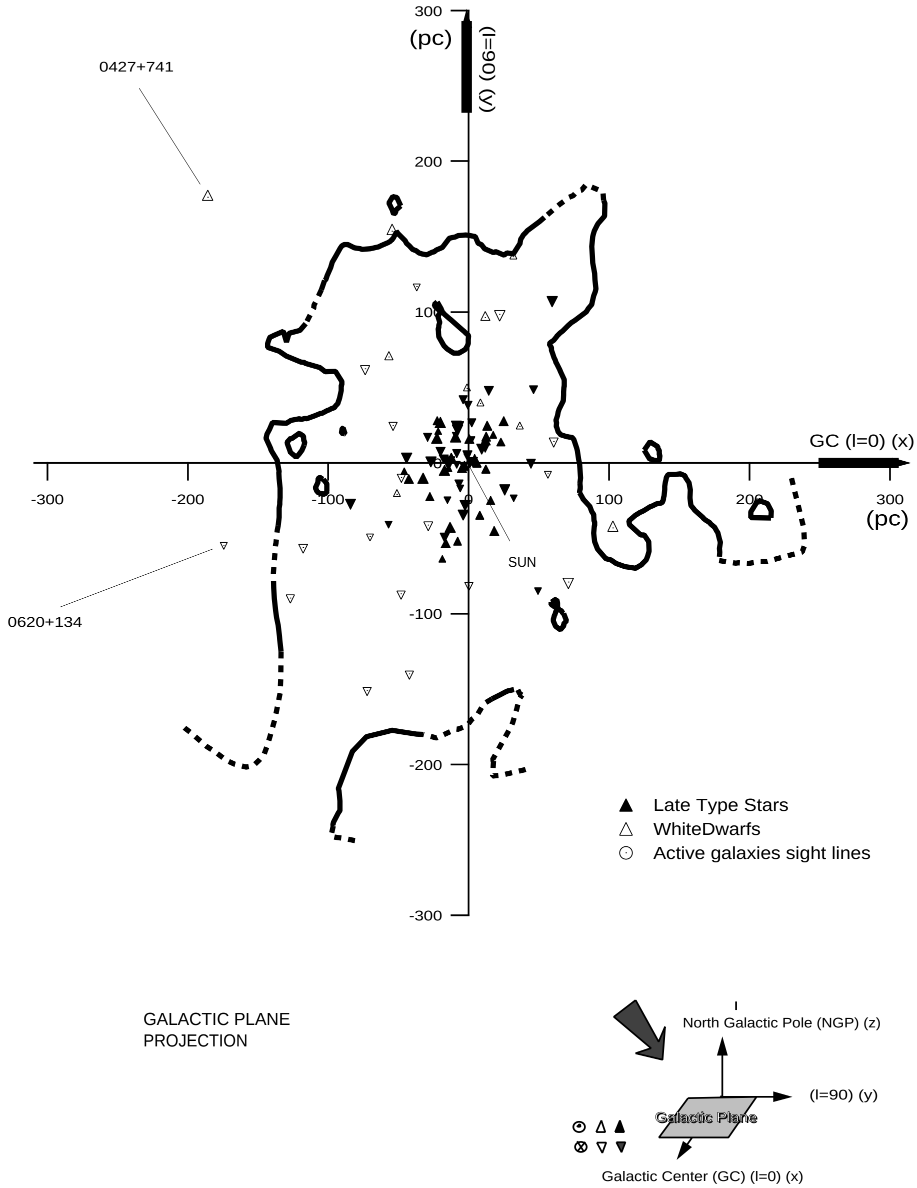

Fig. 5. The distribution of EUV sources with known distances superimposed on the plot of the neutral gas boundary of the Local Bubble in the Galactic Plane (Sfeir et al. 1999).

3.1. Comparison with soft X-ray maps

Maps of the 0.25 keV soft X-ray backgound emission collected by the ROSAT satellite have been presented by Snowden et al. (1997). Sfeir et al. (1999) have found little detailed similarity between the hot local cavity contours suggested by the soft X-ray data and the LB neutral boundary derived from interstellar NaI absorption. The soft X-ray 0.25 keV emission is non-uniformly distributed with significant enhancements found in both galactic hemispheres at high galactic latitudes. A closer inspection of these maps shows that the high latitude peak emission is not centered at $l = 0°$ towards both galactic poles but is offset towards $l \sim 160°$ in the northern hemisphere (the "Lockman Hole" region) and towards $l \sim 330°$ in the southern hemsisphere. We note that the shape of the LB contour shown in Fig. 6 now gives a plausible explanation as to why the soft X-ray background emission enhancements exist in these two directions. This figure clearly shows the LB is open-ended towards both these directions with no dense, absorbing neutral boundary at high latitudes. Fig. 6 also shows the LB (or 'Chimney" as we now should call it) being oriented perpendicularly to the Gould Belt and pointing towards both regions of soft X-ray emission enhancement at high latitudes. We believe that this orientation is no coincidence and suggests that the gas layer in the local arm is tilted in the same way as the Gould belt, in agreement with current theories on its formation (Poppel 1997). The rarefied cavity is still contained within a neutral gas boundary in the galactic plane, but it has now expanded into the lower halo to produce an interstellar feature we now feel is best termed the Local Chimney. Fig. 7 indicates that the chimney is highly elongated (like a wide funnel) at high latitudes in the northern galactic hemisphere. This may explain why the soft X-ray background emission is observed to be distributed over a far wider range of longitudes at high latitudes in the northern hemisphere compared with the southern hemisphere.

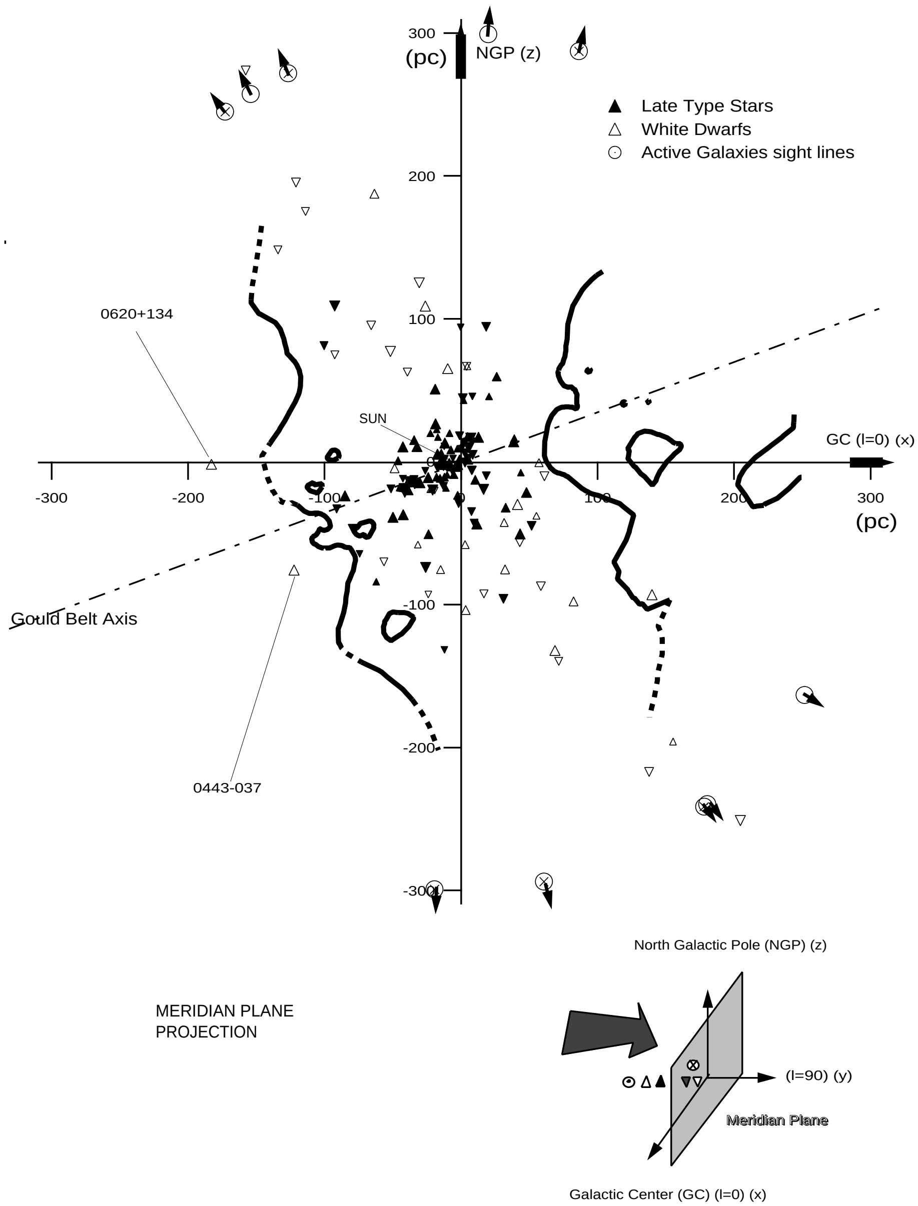

Fig. 6. The distribution of EUV sources with known distances superimposed on the plot of the neutral gas boundary of the Local Bubble in the Meridian Plane (Sfeir et al. 1999).

4. Summary

We have obtained reliable distance estimates for a sub-set of 450 sources detected by the NASA EUVE satellite and shown that $\sim$ 60% of these detections are sources with distances $<$ 50 pc. Active late-type stars dominate the nearby EUV source distribution, whereas the majority of EUV sources with distances $>$ 100 pc are hot white dwarf stars. The galactic distribution of EUV sources is non-uniform with an increase in detections towards several galactic directions that include (a) late-type stars associated with the nearby Hyades cluster at 44 pc, (b) increased source counts towards the region of very low column density in line-of-sight to the star β CMa, and (c) an enhanced number of distant ($>$ 100 pc) EUV sources detected in both hemispheres at high galactic latitudes. A lack of EUV source detections in the region surrounding the Galactic Center is inconsistent with the presence of an intervening dense, neutral interstellar cloud within 20 pc. The deficit of EUV detections in this direction is best explained by the presence of a nearby (d $<$ 20 pc) photo-ionized cloud with an enhanced HeI to H ratio.

We have compared the galactic distance distribution of the EUVE sources with contours of the LB neutral boundary derived from the interstellar NaI absorption data of Sfeir et al.(1999). We find that the vast majority of EUV sources are contained within the nominal LB neutral boundary, thus providing validity to the Sfeir et al. neutral absorption contours. At high galactic latitudes over 20 extragalactic sources have been detected by EUVE along lines-of-sight of low neutral column density that are consistent with the LB being "open-ended" in the galactic halo. This "Local Chimney", which is found to be perpendicular to the Gould Belt, opens towards the regions of enhanced intensity of the 0.25 keV soft X-ray background emission at high galactic latitudes. We conjecture that this orientation is not

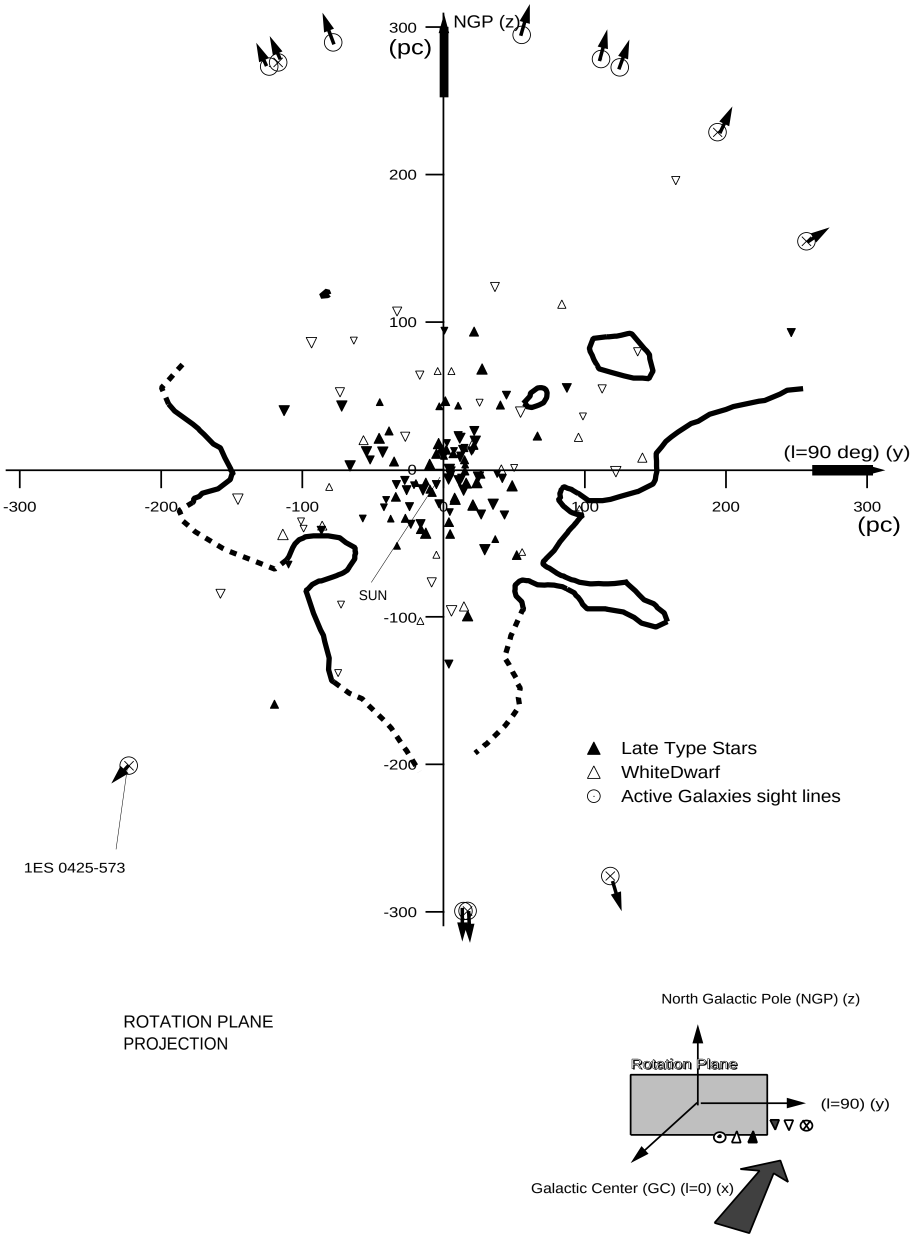

Fig. 7. The distribution of EUV sources with known distances superimposed on the plot of the 'neutral gas boundary of the Local Bubble in the Rotation Plane (Sfeir et al. 1999).

serendipitous and is consistent with the current theory on the formation of Gould's Belt. The local hot gas seems still to be contained within a cold, neutral interstellar gas boundary into the galactic plane, but it has now probably emerged into the halo to produce the Local Chimney feature.

Acknowledgements. We wish to thank the Center for EUV Astrophysics in Berkeley, in particular Dr. Nahide Craig and Dr. Jean Dupuis. We would also like to thank Dr. Steve Snowden (GSFC) and Dr. John Vallerga for very useful discussions. DS and BYW acknowledge funding support through the NASA FUSE program.

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