LARGE SUPERNOVA REMNANTS AS COMMON FEATURES OF THE DISK

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The distribution of the column density of HI over the sky shows strongly organized features of large angular extent. In particular, there is (1) a conspicuous set of arching concentric filaments extending more than 80° on either side of $\ell = 330^\circ$, and (2) a prominent extended region of low column density above $\ell \sim +40^\circ$ and centered on $\ell \sim 130^\circ$. The changes is column density in the b-direction in this region of low N_H is almost step-like at $\ell \sim +40^\circ$.

These distinctly organized structural forms in the two dimensional N_H distribution on the sky imply that there are organized, statistically regular structural forms in the three dimensional space distribution of the gas in the larger neighborhood of the Sun. In this paper models of these statistically regular space structures are described, and the interactions between the ISM and stellar winds, and between the ISM and supernovae that produced the space structures are discussed.

<u>The region of the sky centered at $\ell = 330^\circ$</u>. The arching pattern shown in the HI is also shown by the position angles of optical polarization vectors of nearby stars. In the presentation it was demonstrated that to a very high order of accuracy the HI filaments and the optical polarization vectors are aligned. The magnetic fields that orient the polarization-producing grains lie along or within the elongated space-density structures that we observe as the HI filaments. Position-angle data for the optical polarization vectors serve to determine the center of curvature of the arching structure: $\ell = 331^\circ\!.3 \pm 1^\circ\!.3$, $b = +14^\circ\!.0 \pm 1^\circ\!.4$. Distances of stars whose light is polarized by the aligned grains in the space structures that we observe as arching filaments indicate that the structure extends over the distance range approximately 20 to 400 pc.

Loop I, the large SN shell strongly visible in synchrotron radiation overlaps the arching HI filaments. In the presentation it was shown that the limb of Loop I is remarkably well represented by the projections of a sphere of radius $55^\circ\!.5$, centered at $\ell = 336^\circ\!.0$, $b = +24^\circ\!.0$. The estimated uncertainty of this location is $< 2^\circ$. The centers of the arching filaments and Loop I differ by more than 6σ; Loop I does not

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appear to be the source that created the space-density structure we observe as the HI filaments and that is revealed by optical polarization.

The Sco-Cen Association overlaps the HI filaments. The center of the association is at $\ell = 330^\circ$, $b = +15^\circ$, a point 1.2σ from the center of curvature of the filaments. Sco-Cen is 170 pc distant. It contains more than three dozen stars in the mass range 10-20 $M_\odot$. It is $1 - 2 \times 10^7$ years old. At a distance of 170 pc, Sco-Cen is centrally embedded in the space-density structure we observe as the curved HI filaments. Sco-Cen must be strongly involved with that structure.

A model of the $\ell = 330^\circ$ region. All these observations can be drawn together in a simple physical model. Between 1 and 2×10^7 years ago the rich and rather large Sco-Cen group formed. A considerable amount of left-over interstellar material remained after the stars were formed. This unused material, clumpy and striated in form, distributed throughout the general region surrounding the association, and acted upon by differential galactic rotation over a substantial time interval, had been drawn out into line-like formations generally parallel to the galactic plane and along the local spiral arm or spur. A magnetic field, oriented along the arm, was embedded in these striations. The numerous massive stars in the newly formed association produced strong stellar winds. These inflated a bubble of gas and dust concentric with the Sco-Cen Association. As the striations were swept up on the expanding bubble of wind-driven gas, they were compressed in the radial direction, stretched on the surface of the bubble into the filaments we see today. The near side of the bubble is very close, witness the fact that it subtends an angle of $\sim 170^\circ$. Perspective and shape together produce the observed arching form of the filaments, which are in the surface of the expanding bubble. HI observations indicate that the current rate of expansion is ~ 2 km s^{-1}. Preliminary calculations indicate that the moving bubble contains about 10^6 $M_\odot$ of gas, and represents about 10^{50} ergs of energy; it is approximately 300 pc in diameter.

In this bubble model, Loop I is a SN shell produced by the explosion of one of the most massive members of Sco-Cen. The explosion occurred inside the bubble. Since the medium into which the shell expanded was hot, uniform, and of low density (the bubble has been essentially evacuated by the stellar winds that inflated it) the shell would be expected to be large and closely spherical in form as is observed. The SN shell (Loop I) is just beginning to encounter, and hence to interact with, the inside surface of the HI bubble. Where the SN shell interacts with the bubble, higher velocity features (up to 50 km s^{-1}) are observed. An extensive interactive feature of this type has been found in the Southern Hemisphere by M. Cleary.

The bubble model provides many testable predictions. For example: (1) Given the direction of the center of Sco-Cen and the angular diameter of the bubble (170°) as input data, the form of the arching filaments (or, what is the same thing, the pattern of the optical polarization vectors) can be predicted. The calculations reproduce the observations remarkably well. (2) Given the observed expansion velocity of the HI bubble, ~ 2 km s^{-} , one predicts that pictures of the HI gas in the narrow velocity ranges 0 to -5 km s^{-1}and 0 to +5 km s^{-1}should show the front and back sides of the bubble. The two pictures should be similar in character (arching filaments) but different in detail (different filaments) since the structures are far apart in space ($\sim$ 300 pc) and are uncorrelated. Pictures of the HI in the narrow velocity ranges 0 to -5 km s^{-1}and 0 to +5 km s^{-1}do, indeed, show precisely the behavior predicted.

Observational features of the $\ell = 130^\circ$ region. The most outstanding HI feature in the region of low N_H centered at $\ell \sim 130^\circ$, is a velocity disturbance which is of large amount in velocity and of great angular extent in the sky. This disturbance, which occurs throughout the longitude range $\ell \sim 60^\circ$ to $\ell \sim 220^\circ$, was discovered by the early group at the Department of Terrestrial Magnetism, by the Dutch observers, and others. It was described by Blaauw as existing in both the N and S galactic hemispheres (more pronounced in the N), extending over a large range of longitudes, and being like an approaching stream of gas centered at $\ell = 115^\circ$. The extensive and detailed sky coverage now available in the HI show clearly that this disturbance is not a stream, but is the nature of an extensive shell-like structure having its greatest velocity in the range -50 to -60 km s^{-1}. The shell structure is so pronounced over considerable areas on the North side of the galactic plane that there is little zero-velocity gas.

Loops II and III are conspicuous observational features of the $\ell = 130^\circ$ region visible in synchrotron radiation; they overlap the HI shell structure just described. It has generally been assumed that these loops had their origins in two supernovae which exploded at moderately large z distances (z = 100 to 200 pc), one N of the plane, the other S, at essentially the same time since the loops are similar in size and character. There are no clusters, associations, bright early stars, or any unusual objects in the vicinity of the centers of Loops II and III individually. The unusual requirement of having two simultaneous supernovae on opposite sides of the plane, together with the lack of interesting objects near the Loop centers have always raised doubts about the source or origin of these particular loops.

An important feature of the ISM directly relevant to an explanation of the $\ell = 130^\circ$ region is the great irregularity in the space density distribution of the ISM in the larger neighborhood of the Sun. Lyα observations indicate marked fluctuations in HI density over short distances. The Sun is located in a "hole" of generally low gas density as discussed by Fejes and Wesselius, and others. The nature of the hole can be shown most dramatically with the extensive Hat Creek HI data; the region of minimum gas space density lies in the longitude range 130° to 140°. However, at distances greater than 175 to 200 pc in the second quadrant of longitude there is a steep positive density gradient; in a short distance the gas density becomes greater than the value in the general solar neighborhood by an order of magnitude or more. These general features of the local ISM density distribution (here described for the gas) have long been known to the optical observers.

A model of the $\ell = 130°$ region. The distribution of the intermediate negative velocity gas is statistically regular over the ℓ-range of interest, and forms an expanding bilobed shell. The observed velocity distribution cannot be accounted for by expansion from two centers (two SN, Loops II and III); it demands for its explanation expansion from a single center in or very near the galactic plane.

In the model proposed, then, a single SN event occurred in or near the galactic plane at $\ell \sim 130°$. Because of the nature of the density distribution of the ISM (density greatest in the plane, decreasing with $|z|$), a bilobed structure with axis in the z-direction has been produced. Loops II and III together form the bilobed structure as seen in synchrotron radiation. A picture of HI in a restricted velocity range (which enhances the shell structure and makes it more visible) likewise clearly shows the bilobed structure in the HI gas surrounding the synchrotron radiation.

In this simple explosion model the direction assigned places the star that exploded in the α Per Association. The α Per Association, age $\sim 10^7$ years, is ~ 150 pc distant; it contains about a dozen stars more massive than 10 solar masses, the mass of the moving intermediate negative velocity gas is $\sim 10^3$ $M_\odot$; the kinetic energy of the gas is $\sim 10^{50}$ ergs.

The proposed bilobed model is a very rich one; it provides many predictions open to test and, together with the observed density distribution of the ISM, provides explanations of many phenomena observed in this region of the sky as, for example, the expanding "ring" of HI discovered by P. O. Lindblad, and the classic high velocity gas discussed by Oort. Lack of space precludes discussion of these and other topics; they will be considered in detail elsewhere.

DISCUSSION

Oort: If high-velocity clouds are connected with huge expanding shells, the approaching (negative-velocity) parts should be very nearby, at distances not much larger than 100 pc. In the few cases where interstellar absorption lines have been observed, the distances appear to be rather larger. In particular, the so-called feature A is inferred from the lack of interstellar absorption lines at its velocity (of about 200 km s^{-1}) in two stars at estimated distances of 500 and 1500 pc, respectively, to be much too distant to be part of a shell of the type you have discovered. The absorption-line data are unfortunately still extremely meager, and it is quite possible that part of the intermediate velocity gas and the high-velocity gas in the arc-like structure formed by the high-velocity features CI, CII, CIII which you showed should be interpreted in the way you have suggested.

Weaver: The question of distance of the high-velocity clouds (or of features clearly associated with them) remains as a very important observational problem. One of the strengths of the model I have presented is that it suggests new approaches to this problem--approaches that will involve optical polarization and various other observational data. I believe that feature A is one of the objects that can be investigated by new methods.

van den Bergh: You say that these structures have ages of $\sim 10^7$ year. During such a time period one would expect $\sim$ 500 supernovae per kpc^2 to explode. This would seem to make it a bit difficult to associate your arcs with a single supernova outburst.

Weaver: The arcs are not associated with a supernova outburst. They are parts of the bubble of gas blown by the stellar winds originating from the Sco Cen Association. The stars in Sco Cen are now in process of going off as supernovae--at least those of the stars that have sufficient mass to become supernovae--and they very likely will change or destroy the bubble eventually. In my model, Loop I is a shell from a supernova that originated from one of the members of the Sco Cen. It exploded inside the bubble in a very hot, tenuous atmosphere. The SN shell is now starting to interact with the inside of the bubble. It and the other SN shells that will in the future develop from the Sco Cen stars will probably destroy the bubble, but we see the bubble now because of the stage of development of Sco Cen.

It is, I believe, an error to use statistics as implied in this question. In any specific 10^7 years not every kpc^2 of the Galaxy is equally likely to produce SN. We do know where clusters and associations around us are located, and we know which ones are likely to produce SN. As an analogy to these broad statistics just quoted, the average birthrate in the U.S. is one child per 2 square miles per year. But not all areas of 2 square miles--the top of Pike's Peak or the middle of Lake Erie--are not, at least during the present geologic era, likely to produce the average number of births.

Cesarsky: An alternative explanation, existing in the literature, of the observed arches which are aligned to the magnetic field, is that they are the end result of the Parker instability in the galactic disk. As our calculations imply that the end result of the Parker instability is not a collection of stable arches, I am pleased that another, more convincing explanation of these features has been presented.

Weaver: I have also worried about the Parker instability explanation of the arching filaments seen on the sky. I was very pleased to be able to propose an alternative explanation.

Burke: I just checked with Dr. Salpeter, and he agrees that supernova shells do not ordinarily last 10^7 years. A million years is a better number and so multiple SN remnants are not as common as Dr. van den Bergh suggested. By 10^7 years, the shells are well thermalized.

Weaver: The shell around the Sco Cen Association I described was not produced by a supernova; it was produced by stellar winds from the Sco Cen Association. The SN shell within the Sco Cen bubble and the SN shell producing the intermediate velocity and high velocity gas are both much younger than 10^7 years. They are probably not more than 10^5 to 10^6 years old. It is certainly probable that they will become thermalized in 10^7 years.

Felten: You have rather definite kinematical models for the three structures you discussed: Can you say something about the ages of these structures, on the basis of the model kinematics? Is your estimate of 10^7 years for the age of the large structure based upon the kinematics, or simply upon the notion that is started when the SCO-CEN association was formed?

Weaver: It will be possible to make some reasonable age estimates by means of the kinematics of the models. It has not yet been done. The age I quoted for the Sco Cen shell is based only on the age of the association.

Assousa: In primordial times of 1975, in a lecture at Berkeley discussing your early results observationally linking HI shells with known Galactic supernova remnants, Professor Minkowski was skeptical! We have come a long way through our understanding of such structures in HI surveys, typified by the work of Professors Weaver and Heiles. Noting that these shells provide coherent large-scale structures in our Galaxy, having masses $\sim 10^4\ M_\odot$ and lasting $\gtrsim 10^6$ years, I suggest that we begin to think of such objects as important "unit" components--in the same way we treat Giant Molecular Clouds of mass $\sim 10^5\ M_\odot$.

Weaver: I quite agree. I think we must come to realize that giant star clusters and associations can and will be organizers of the kinematics and structure of the surrounding gas.

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