Deep Hα imagery of the Eridanus shells

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ABSTRACT

A deep Hα image of interlocking filamentary arcs of nebulosity has been obtained with a wide-field (≈ 30° diameter) narrow-band filter camera combined with a CCD as a detector. The resultant mosaic of images, extending to a galactic latitude of 65°, has been corrected for field distortions and had galactic coordinates superimposed on it to permit accurate correlations with the most recent H1 (21 cm), X-ray (0.75 kev) and FIR (IRAS 100 μm) maps.

Furthermore, an upper limit of 0.13 arcsec/yr to the expansion proper motion of the primary 25° long nebulous arc has been obtained by comparing a recent Hα image obtained with the San Pedro Martir telescope of its filamentary edge with that on a POSS E plate obtained in 1951.

It is concluded that these filamentary arcs are the superimposed images of separate shells (driven by supernova explosions and/or stellar winds) rather than the edges of a single ‘superbubble’ stretching from Barnard’s Arc (and the Orion Nebula) to these high galactic latitudes. The proper motion measurement argues against the primary Hα emitting arc being associated with the giant radio loop (Loop 2) except in extraordinary circumstances.

Key words: interstellar medium; Eridanus shells
1 INTRODUCTION

A 25° diameter area of interlocking arcs of Hα emitting filamentary nebulosity was discovered (Meaburn 1965, 1967) projecting from the galactic plane to high galactic latitudes ($b = -50°$). The primary nebulous arc (hereafter called Arc A) is traced from $(l, b) = (180°, -30°)$ to $(l, b) = (200°, -50°)$ (in the Eridanus constellation) and has a similar morphology to the emission regions associated with old supernova remnants (Meaburn 1967). For this reason an association of Arc A with one of the giant radio loops (the 90° diameter Loop 2, Large et al. 1962, Haslam et al. 1971) was suggested, in which case, Arc A could have been within 30 pc of the Sun. Reynolds & Ogden (1979), henceforth RO, though suggested that the arcs were edges of a single elongated cavity expanding at $\approx 15$ km s$^{-1}$ and extending from the I-Ori OB-association and therefore at the greater distance of $\approx 450$ pc. They cite the proximity of the well-known ‘Barnard’s Arc’ (see Sivan 1974) in support of this contention. Since this early work the Eridanus nebulosity has continued to receive considerable attention in many other wavelength domains largely because an uncluttered view of the closest galactic interstellar shells is permitted at such high galactic latitudes.

More recently, data from the Leiden/Dwingeloo HI survey (Hartmann & Burton 1997, Burton & Hartmann 1994), the IRAS Sky Survey Atlas ISSA (Wheelcock et al. 1994) and ROSAT X-ray survey (Burrows & Guo 1996, Snowden et al. 1995) have provided a more detailed picture of the region. Comprehensive comparisons between the data sets have been made by Burrows et al (1993), Brown et al (1995), Heiles et al (1998) and Heiles et al (1999). They suggest a similar unifying picture of the region similar to that given by RO - a large superbubble (SB) filled with hot X-ray emitting ($T \approx 1 \times 10^6 K$) gas extending from the Ori OB1 association at a distance of $\approx 450$pc, with the nearest edge at $\approx 150$pc. Burrows & Guo (1996) estimated a distance of $159 \pm 16$pc in the direction $(l, b) = (200°, -47°)$. The cavity is enclosed in an expanding neutral shell traced between $-40 \text{ km s}^{-1} \leq v_{\text{lsr}} \leq +40 \text{ km s}^{-1}$ which is seen preferentially edge-on. However, the structure of the ‘Eridanus-Bubble’ and its formation are still under scrutiny. Heiles et al (1999) has pointed out that it is clear that there are some dependencies on other nearby shells including the local ‘superbubble’ (SB), in which the Sun is immersed. However, the filamentary Arc A does not fit clearly into this simple SB picture. For one thing, its curvature is in the opposite sense to that predicted by the SB model.

Deep, narrow-band, Hα images have been obtained with a wide-field CCD camera of the
Eridanus nebulosity to permit a more detailed, and astrometrically accurate, comparison with features at other wavelengths. Furthermore, a new upper limit to the proper motion (pm) of the sharp filamentary edge of Arc A has been obtained in an attempt to constrain the lower limit to its distance. The previous measurement (Jones & Meaburn 1985) used material over a shorter baseline and with a lower signal-to-noise ratio.

2 OBSERVATIONS AND RESULTS

2.1 Wide field imagery

The layout of the Manchester Wide Field camera (MWFC) is shown in Fig. 1. A $21^\circ \times 30^\circ$ field-of-view is converted to $5.5^\circ \times 7.8^\circ$ for acceptance in the parallel beam by a three-period (square profile) interference filter, of $16\,\AA$ bandwidth centred on $H\alpha$. The field is finally imaged on to a Wright Instrument, nitrogen cooled, CCD with $385 \times 578$ pixels giving a scale of $\sim 3.29\,\text{pixel}^{-1}$. The observations reported here were made at Kryonerion Observatory in Greece, between 12–16 of December 1996.

The eight fields covered and the integration times used are listed in Table 1. The negative grey-scale representations of the final mosaic is shown in Fig. 2. The galactic coordinates are accurate to a few arcmins for the images were processed (Boumis 1997) using the Starlink KAPPA packages CENTROID and SETSKY, the IRAS90 packages SKYALIGN and SKYGRID and the mosaicing CCDPACK package MAKEMOS. All the astrometry information can then be displayed in the final image using SKYGRID. In particular, optical field distortions were corrected in this process.

The $H\alpha$ emitting regions in Fig. 2 are compared with the 100 $\mu$m IRAS emission in Fig.
3(a) and with both the ROSAT X-ray (kev band) emission and the HI 21 cm ring (Brown et al. 1995) in Fig. 3(b). The principal Hα arcs are called Arcs A & B in Fig. 3(a).

2.2 Proper motions

The brightest part of the filamentary Arc A has a sharp edge in the light of Hα. This appears somewhat faintly on the Palomar Observatory Sky Survey (POSS) Schmidt plate E232, taken on the 3rd of January 1951. Nonetheless the area containing Arc A was digitized with the PDS scanning microdensitometer at the Royal Greenwich Observatory (RGO). The resulting image measured 250 × 250 pixels with a resolution of 20 μm (≡ 1.34″).

In an attempt to measure any proper motion of Arc A this same filamentary edge was imaged (see Fig. 4) on the 8th of November 1996 with the 2.1m San Pedro Martir (SPM) telescope in Mexico. The integration time was 1800s through an interference filter centred Hα and with an 11Å bandwidth with the Tek CCD, (1024 × 1024, 24 × 24 μm² pixels to give a scale of 0.3″ pixel⁻¹ at the f/8 focus) as the detector. The resultant ‘seeing’ disk was 1.8″ diameter nearly matching the POSS resolution.

The Starlink CCDPACL package ccdalign was used to align the two data arrays and the GAIA package PATCH to then remove the star images. Both arrays were finally rotated by the same amount until the filamentary edge was vertical in both. Brightness profiles were compared for a cut, 2.15′ long and marked in Fig. 4, perpendicular to the most defined part of the filamentary edge of the nebulous Arc A. These are shown in inserts in Fig. 4. A conservative upper limit to the proper motion, perpendicularly to the filamentary edge, of \( \pm 0.13 \)″ yr⁻¹ was given with the detection limit governed by the lower signal-to-noise ratio in the POSS data.

3 DISCUSSION

There is an immediate implication of the expansion pm upper limit for Arc A in Sect. 2.2. Consider a pm of \( \delta \theta \) arcsec yr⁻¹ for a filament with a tangential velocity of \( V_t \) km s⁻¹ at a distance D pc then \( D = 4.612 \frac{V_t}{\delta \theta} \) pc. If Arc A is the edge of a shell expanding slowly at 15 km s⁻¹ then for an expansion pm of \( \leq 0.13 \) arcsec yr⁻¹ its distance must be \( \geq 530 \) pc. The 25° long Arc A would have a linear extent of \( \geq 230 \) pc with this lower distance limit. Any higher expansion velocities than 15 km s⁻¹, such as those of \( \geq 50 \) km s⁻¹ typical of old supernova remnants (Cygnus Loop, IC443, Vela etc) and capable of causing collisional
ionization, would then place Arc A at the improbably high distance of $\geq 1.8$ kpc with a corresponding increase in linear size.

The relationship of Arc B to both Barnard’s Arc and Arc A should now be considered. Firstly, Heiles et al (1999) show that an area of soft X-ray emission mapped by Snowden et al (1995) extends from Barnard’s Arc (15° diameter centred on $(\ell, b) = (224.5^\circ, -18^\circ)$ and the Orion Nebula) to Arc B. In fact they describe this volume as the ‘Eridanus superbubble’ with Arc B as the supershell wall. The detailed correlations shown in Fig. 3(b) suggest an alternative interpretation. Here, Arc B appears to be one edge of a self-contained shell delineated by the 20° diameter ring of HI 21cm emission surrounding a localised enhancement of super-heated X-ray emitting gas. Warm dust, giving rise to the 100 $\mu$m ridge just outside Arc B, must be mixed with the neutral gas piled up as the HI shell expanded. A separate shell is suggested which appears to be unrelated to Arc A and not to be part of a coherent, elongated ‘supershell’ emanating from the Orion region. In fact this shell could be one of a complex of shells whose overlapping images give rise to the more extended X-ray region.

The mechanism for the ionization of the H$\alpha$ emitting region of Arc B must be considered within the model that this ionized shell of gas is on the inside surface of the larger 20° diameter HI shell. An expanding supernova remnant, with a shock driven into the surrounding interstellar medium would have exactly the reverse of this configuration if its expansion velocity was great enough to generate a radiative shock ie H$\alpha$ emitting filaments would be expected on its outside surface. Furthermore, leakage Lyman photons from the Orion nebula are shielded from this inside surface by the outer HI shell. It can be seen in Fig. 3(b) that an arc of X-ray emitting, super-heated, gas is immediately adjacent to Arc B. This hot gas is most likely the slowly cooling remnant of the shocked blast wave that originally pressured the expansion of the shell in its early, energy conserving, phase (assuming a supernova origin) and is still present in the shell’s present momentum conserving phase.

The X-ray emitting gas is most strongly located towards higher galactic latitudes within the HI shell. In general, the random motions of HI clouds do not allow them to rise to much more than 100 pc or so from the galactic plane. Hot ($\sim 10^6$ K) X-ray emitting gas will have a much larger scale height above the galactic plane due to the high sound speed in gas of this temperature. The scale height is about (Kahn 1998) $c_H^2/g_z$, where $c_H \approx 100$ km s$^{-1}$ is the sound speed in the hot gas and $g_z \sim 10^{-8}$ cm s$^{-1}$ is the gravitational field directed down towards the disk. This buoyancy of the hot gas within the HI shell may then have resulted in the hot gas gathering at the top (with respect to the galactic plane) of the shell. If the hot gas
has enough pressure to eventually be able to break through the H\textsubscript{I} shell that is constraining it then it will be able to rise into the galactic halo, forming part of the galactic fountain and leaving a chimney structure behind (see e.g. Norman & Ikeuchi 1989). Photoionization by the Lyman photons in the long wavelength wing of the $10^7$ K Black Body emission from the super-heated gas is a possible ionizing mechanism. More likely the optical emission seen at the interface between the hot and cold gas arises as a result of mixing between the two media. This can occur via thermal conduction (see e.g. Borkowski, Balbus & Fristrom 1990, and references therein) as hot electrons heat and ionize the inner edge of the H\textsubscript{I} shell giving rise to a warm layer of $\sim 10^5$ K. This is a thermally unstable temperature and the gas will rapidly cool to $10^4$ K resulting in the emission of H\alpha. Thermal conduction may be inefficient if significant magnetic fields are present that can hinder the transport of hot electrons to the cold gas or if there is significant relative motion between the two media (Hartquist & Dyson 1993). If this is the case, then mixing can take place via localised boundary layers and shocks (Dyson et al 1993, Redman et al 1999). An observational test that these effects are still taking place would be the detection of O\textsc{vi} absorption lines since this ion indicates temperatures of $3 - 5 \times 10^5$ K which, as mentioned above, is a temperature from which material can rapidly cool.

Incidentally, the best guide to understanding these structures extending from Barnard’s Arc to Arcs A and B in Fig. 2 and the extended X-ray emitting gas must be the giant shells of the Large and Small Magellanic Clouds and six interlocking shells between 68-308 pc diameter in the Local Group galaxy IC 1613 (Meaburn et al. 1988). For one thing their dimensions correspond to those of Arcs A and B for distances $\geq 530$ pc. The image of such a group of separate shells, viewed from the edge of the group, but within the plane of a galaxy, would appear as overlapping H\textalpha emitting filaments along any sight-line or in X-rays, by superimposed emission from separate volumes of super-heated gas.

Arc A in Fig. 3(a & b) could then be unrelated to Arc B and similarly not part of an elongated ‘superbubble’ projecting from Barnard’s Arc: it could simply be the manifestation of a further shell whose image is superimposed on Arc B. The original correlation of Arc A with the giant (90° diameter) non-thermal radio loop (Loop 2 - Meaburn 1965 and 1967) now seems unlikely in view of the present upper limit to its expansion proper motion. Only if Loop 2 were a truly fossilised, nearby, supernova remnant with an expansion velocity of $\leq 10$ km s\textsuperscript{-1} could Arc A exist within the requisite 30 pc of the Sun. In this case ionization of the outer edge of a compressed H\textsubscript{I}, 90° diameter, swept-up shell by leakage Lyman photons from
the 450 pc distant Orion region would also have to be invoked to produce the observed Hα emission. The sense of the curvature of Arc A is one feature in favour of this interpretation. A relationship of Arc A with the nearby, separate HⅠ shell found by Lindblad et al (1973) cannot be ruled out.

4 CONCLUSIONS

We calculate a lower limit of 530pc to the distance of Arc A by assuming an expansion velocity of $\approx 15 \text{ km s}^{-1}$ (RO, 1979). This corresponds to a linear size of $\geq 230\text{pc}$. Arc B could be at a much lower distance of $\approx 150\text{pc}$ and seems to be self-contained in a 20° diameter HⅠ ring. Therefore we have evidence for Arc A and Arc B to be part of a complex of individual shells viewed along the same sight-line, and therefore not just the edge of a single Eridanus superbubble. Further fainter arcs and loops can also be seen in the deep Hα mosaic image at a lower level, supporting this hypothesis. Furthermore, a complex of interlocking shells of this size and morphology, is consistent with similar structures seen in the LMC and SMC.

The mixing of extended soft X-ray emission with the HⅠ shell wall (adjacent to Arc B) is argued to be the most likely ionising mechanism for Arc B.

Arc A on the other-hand, could still be related to giant radio Loop 2, but only for expansion velocities $\leq 10 \text{ km s}^{-1}$.

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5 FIGURE LEGENDS

Figure 1.
The optical layout of the Manchester wide field camera (MWFC). The interference filter is in the exit pupil.

**Figure 2.**
A negative grey-scale representation of the mosaic of Hα images taken of the Eridanus nebulosity.

**Figure 3(a).** A comparison of the Hα contours (linear intervals) from the image in Fig. 2 with a negative grey-scale representation of the IRAS 100 μm image of the field. Arcs A & B are indicated.

**Figure 3(b).** A lighter grey-scale representation of the Hα image in Fig. 2 is compared with the ROSAT X-ray (0.75 kev) contours. The Hı ring is indicated by a dashed line from Brown et al (1995).

**Figure 4.**
A negative Hα image of the sharp edge of Arc B taken with the San Pedro 2.1m telescope is shown. This has been rotated to bring the sharp edge of Arc A nearly vertical in the data array. The field centre is RA = 04h 01m 21.47s DEC = +01° 32’20.5” (J2000) (ℓ, b) = (188.7°, -36.1°). Note that north is to the top of the tilted left-hand edge of the image. Cuts taken across the Hα filament from (a) the SPM telescope and (b) the POSS data arrays are shown as inserts. These were co-additions from the respective images for the length marked against the image of the filamentary edge.

**REFERENCES**

Borkowski K. J., Balbus S. A., Fristrom C. A., 1990, ApJ, 355, 501

Boumis P., 1997, PhD thesis, The University of Manchester

Brown A.G.A., Hartmann D. & Burton W.B., 1995, A&A, 300, 903

Burrows D.N., Singh K.P., Nousek J.A., Garmire G.P & Good J., 1993, ApJ, 406, 97

Burrows D.N. & Guo Z., 1996, MPE report, 263, 221

Burton W.B. & Hartmann D., 1994, Ap&SS, 217, 189

Dyson J. E., Hartquist T. W., Biro S., 1993, MNRAS, 261, 430

Hartmann D. & Burton W.B., 1997, Atlas of Galactic Neutral Hydrogen, Cambridge University Press.

Hartquist T. W., Dyson J. E., 1993, QJRAS, 34, 57

Haslam C.G.T., Kahn F.D. & Meaburn J., 1971, A&A, 12, 388

Heiles C., 1998, in Proc. of IAU Colloqium, no. 166, “The Local Bubble and Beyond”, eds. D. Breitschweidt, M.J.Freyberg and J. Trümpner

Heiles C., Haffner L.M., Reynolds R.J., 1999, ASP Conference Series, vol. 168, p. 211

Jones A.W. & Meaburn J., 1985, MNRAS, 213, 711

Kahn F. D., 1998, in Breitschweidt D., Freyberg M. J., Trümper J., eds, The Local Bubble and Beyond - Lyman Spitzer Colloquium: Proc. IAU Col. 166. Springer, p. 483 (Lecture notes in Physics, Vol. 506)
Large M.I., Quigley M.J.S. & Haslam C.G.T., 1962, MNRAS, 124, 405
Lindblad P. O., Grape K., Sandqvist Aa. & Schober J., 1973, A&A, 24, 309.
Meaburn J., 1965, Nature, 208, 575
Meaburn J., 1967, Zeits. Astrophysik., 65, 93
Meaburn J., Clayton C.A. & Whitehead M.J., 1988, MNRAS, 235, 479
Norman C. A., Ikeuchi S., 1989, ApJ, 345, 372
Redman M. P., Al-Mostafa Z. A. A., Meaburn J., Bryce M., Dyson J. E., 1999, A&A, 345, 943
Reynolds R.J. & Ogden P.M., (RO), 1979, ApJ, 229, 942
Sivan J.P., 1974, A&AS, 16, 163
Snowden S.L., Burrows D.N., Sanders W.T., Aschenbach B. & Pfeffermann E., 1995, ApJ, 439, 399
Wheelcock S.L., Gautier T.N., Chillemi J., et al., 1994, IRAS Sky Survey Atlas Explanatory Supplement, Jet Propulsion Laboratory, Pasadena
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