# INTERSTELLAR NEUTRAL HYDROGEN FILAMENTS AT HIGH GALACTIC LATITUDES AND THE BENNETT PINCH

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**Abstract.** Observed properties of interstellar neutral hydrogen filaments suggest the presence of the Bennett pinch as described by the Carlqvist relationship with rotation around the filament axes included. A brief summary is first given of three ways in which a filament model for interstellar "cloud" structure was tested. Preliminary results from highresolution HI mapping of gas and dust in an apparent HI "cloud" indicate that the neutral gas and dust within and around its boundary is itself highly filamentary. An attempt to detect magnetic fields in this and similar features using the Zeeman effect technique at the 21–cm wavelength of interstellar neutral hydrogen set upper limits of a few $\mu$G. In contrast, the strength of the toroidal magnetic field expected from the examination of the Carlqvist relationship is of order 5 $\mu$G, which would be produced by a current of $1.4 \times 10^{13}$ A. Zeeman effect technology is at present not able to detect toroidal magnetic fields of this order at the edge of barely resolved HI filaments. Nevertheless, currently available high–resolution HI data suggest that interstellar filament physics should take into account the role of currents and pinches for creating and stabilizing the structures.

## 1 Introduction

Neutral hydrogen (HI) surveys at high galactic latitudes show that the interstellar gas is filamentary; see for example Verschuur (1973, 1974a, 1974b, 1991a, 1991b) and Verschuur *et al.* (1992). The filamentary nature of the HI is also dramatically evident in the data by Colomb, Pöppel, and Heiles (1980) and the new all–sky Leiden–Dwingeloo HI survey (Hartmann, 1994). What, then, is the relationship between such fialments and magnetic fields that thread their way through interstellar space? And is it possible that the origin and stability of the filaments depends on the existence of large–scale currents as found by Carlqvist and Gahm (1992).

Verschuur (1991a) has shown that morphological waves with wavelengths of order 30° and amplitude $\sim 1/8\lambda$ exist in several HI filaments in a 540 square degrees of sky around $l$=230°, $b$=+40°. The extent of the longest filament is greater than 72°, the limit set by the boundaries of the area surveyed. The motion within the filaments, determined by analysis of velocities along their axes, suggests the presence of wave patterns with amplitude 5 to 6 km/s on an angular scale similar to that seen in the spatial wave–like structure projected on the sky. Furthermore, in this area of sky every so-called HI "cloud" (or enhanced emission feature; EEF) is found to be associated with a filament while the "clouds" are usually found where the filaments show

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changes in the orientation of their axes, as if defining kinks in the filaments. This raised the interesting possibility that a "cloud" of diffuse interstellar HI, defined by a localized enhancement of HI emission, might be a geometric illusion produced where a segment of filament twists into the line of sight. Our study began in order to test this simple model.

An example of an HI "cloud" is shown in Figure 1. Each frame plots the distribution of the antenna temperature of the HI emission at the velocity indicated at the lower right of the frame (in km/s with respect to the local standard of rest). The original maps were plotted with a resolution of 20 arcmin (Verschuur 1974a). The lower right frame shows a sketch of the derived filamentary patterns taken from Verschuur (1991b). The numbers in this frame indicate the velocity of the HI emission at various locations along Filament A whose morphology is derived by reference to the HI structure in the other frames.

The bright feature in the center of the various maps is an example of an EEF ("cloud"), this one labelled H0827+10. At the extreme velocities at which it is identified it appears to be connected to material at the top-right and lower-left of the area shown here. If filament geometry accounts for EEFs, H0827+10 may represent a direction in which the filament twists into the line-of-sight.

We have carried out three types of observations to test this hypothesis. First, if cool interstellar HI and dust are associated, we might obtain a better view of the filament geometry by examining the distribution of 100 $\mu$ emission from the dust, since the IRAS survey of 100 $\mu$ emission has a resolution of a few arcmin, considerably better than most radio telescopes used in the study of interstellar HI structure. Second, high-resolution HI mapping should show the structure more clearly. The third test involves mapping the magnetic field in the direction of the EEF using the 21-cm Zeeman effect as a probe. This experiment is sensitive to the line-of-sight component of the magnetic field and if EEFs are illusions produced where a segment of filament twists into the line-of-sight, the magnetic field should appear stronger toward in the EEF than toward its surroundings. We briefly report on the result of all three tests.

## 2 The Data

Figure 2 shows the 100 $\mu$ flux from cool interstellar dust in the direction of the EEF H0827+10, the bright feature at the center of this map. The presence of filaments is obvious and it is not difficult to imagine that even on this scale the brightest features are produced where filaments overlap or twist into the line-of-sight. When the central part of Figure 2 is examined more closely under different contrast, the brightest feature is seen to have a loop shape.

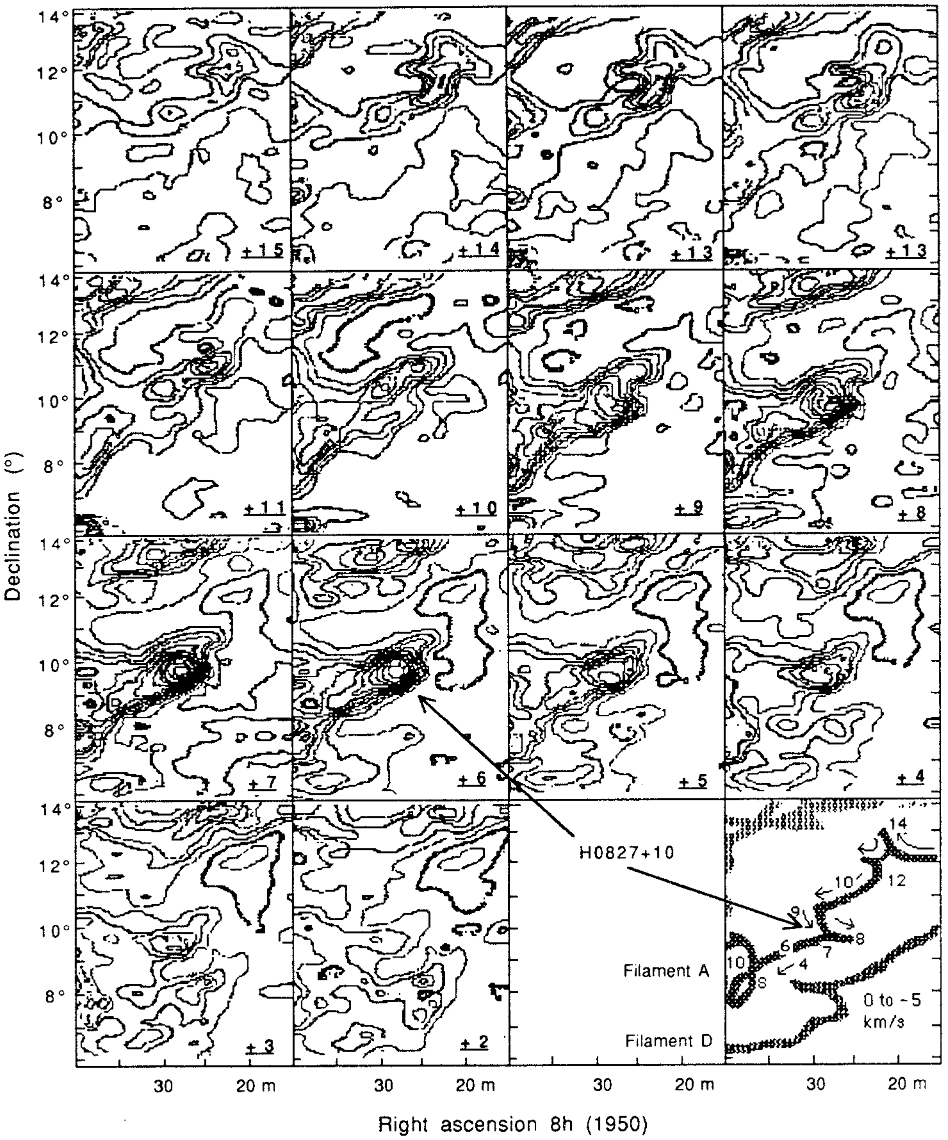

Fig. 1. Neutral hydrogen maps at various velocities of a small area of sky around the feature labelled H0827+10 (indicated by the arrows) taken from an area survey made by Verschuur (1974a). The velocity is indicated at the lower right of each frame. The lower-right frame is a schematic representation of several filaments that cross this field of view taken from Verschuur (1991b). The numbers indicate the velocity of the gas at various locations along Filament A. H0827+10 would traditionally be referred to as a "cloud."

The Arecibo radio telescope was next used to obtain high resolution (4 arcmin) maps of the HI emission from H0827+10. Our analysis technique involved the Gaussian decomposition of hundreds of profiles in order to iden-

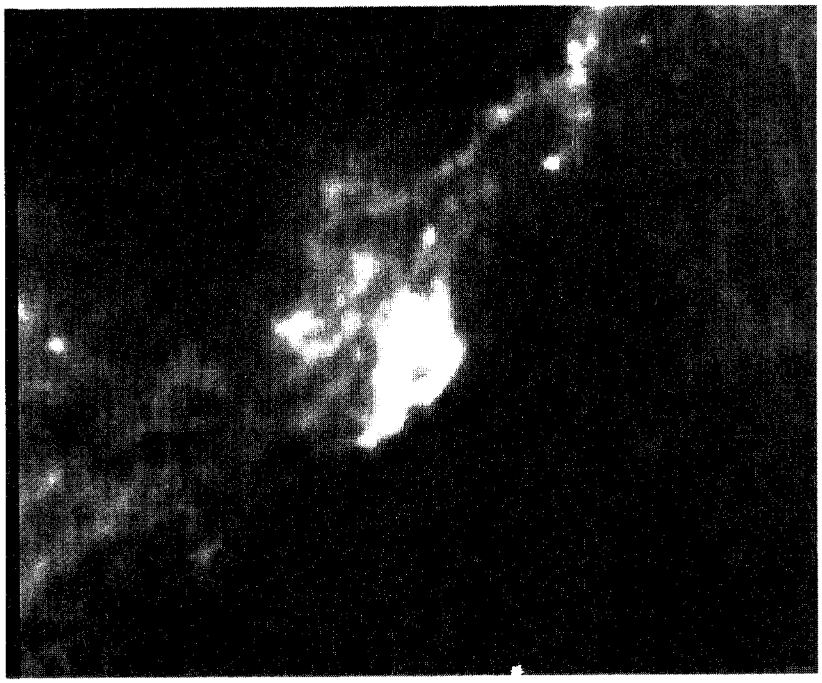

Fig. 2. The 100 HI emission from cool dust associated with the HI feature H0827+10. The image size is 4° x 5° centered on right ascension 8h 27m, declination +9° 48'. The dust shows a great deal of filamentary structure not visible in the lower resolution HI data in Figure 1. In a display using different contrast, the brightest feature is seen to be a distinct narrow loop. There is no indication of the existence of a clearly bounded, cloud-like entity in this region.

tify families of components and then making an area map of each component before comparing the results with the 100 $\mu$ data. Figure 3 shows the combined column density of cool gas found in three of the brightest Gaussian components defining the emission profiles in this region. Comparison of Figures 2 and 3 shows a great deal of similarity, certainly within limits set by the resolution and data display techniques. It is striking that the HI map appears on the verge of revealing as much detail as is seen in the 100 $\mu$ data. A similar map of the total HI column density shows far less contrast, due in part to the presence of unrelated gas along the line–of–sight, and to lesser extent to the unwanted influence of sidelobes distorting the emission profiles at low levels. The morphological similarities between the structures seen inf Figures 2 and 3 suggest that this way of analyzing the data is more powerful than the traditional method of comparing total HI column density with 100 $\mu$ brightness.

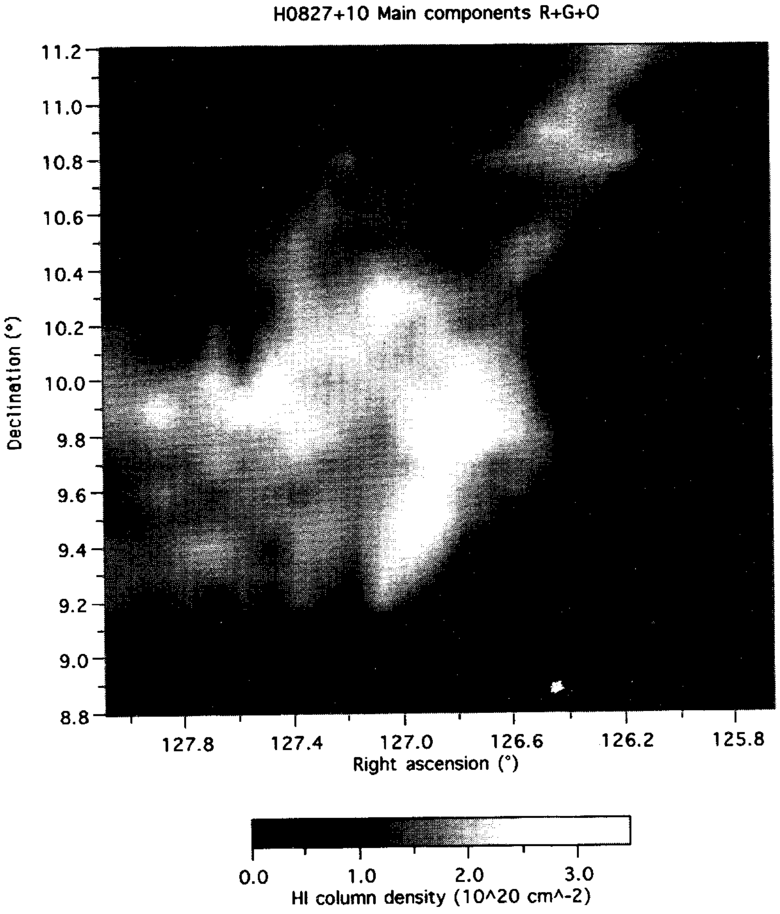

Fig. 3. Gray-scale image of the combined HI column density in units of $10^{20}$ cm$^{-2}$ in three Gaussian components most clearly defining the HI feature H0827+10 based on the high-resolution survey referred to in the text. Comparison with Figure 2 shows the high degree of morphological similarity between the 100 emission and the HI structure. This HI image is on the verge of revealing as much detail as is seen in Figure 2. Two dark rectangles indicate areas of missing data at the top-left, down to declination 10.°2, and at the topcenter, down to 10.°75. Right ascension 127° is 8h 28m.

Figure 3 shows that the the HI "cloud" H0827+10 in Figure 1 contains enhanced filamentary structure and that the original "cloud" is not a physically bound, coherent entity at all, at least not in the sense that some unifying force, whether gravity or a simple magnetic field configuration, gathers the gas into a small, spherically symmetric volume of space. It seems likely that the enhancement in brightness in the lower resolution HI data is related mainly to line–of–sight geometrical effects while revealing little about the possible physics involved in creating the structure. (Bear in mind that the structure seen in these maps is not two-dimensional but has an unknown depth component).

Our third test of the twisted filament model involved observations of the Zeeman effect in HI emission profiles (Verschuur, 1995a,b). The goal was to find evidence for magnetic fields in the 5–20 $\mu$G range, which could control gas motion in the filaments (Verschuur 1991b). Various observers such as Troland and Heiles (1982) and Heiles (1989) claimed that magnetic fields this strong exist in diffuse HI. Instead of confirming their results or adding to the data base, our study revealed the presence a systematic problem that has affected all such observations. After making appropriate corrections to the data, no evidence for magnetic fields in the 5–20 $\mu$G range in diffuse HI emission is found anywhere in the sky (Verschuur, 1995a,b). The only magnetic fields in interstellar space of this order that have been observed are associated with dense HI structures ("clouds") adjacent to star forming regions, where the magnetic fields may have been amplified by shock compression (see Verschuur 1995c for a summary).

For H0827+10 the Zeeman effect observations give a value forthe line–of–sight magnetic field strength of -0.7 + 1.0 $\mu$G (one sigma error) toward the brightest feature in Fig. 3. The average magnetic field for five directions sampled in H0827+10 is -0.1 + 0.6 $\mu$G. This implies an upper limit of ~2 $\mu$G. Upper limits of 1.4 $\mu$G have been set for two other EEFs, while a third gave 0.6 $\mu$G (Verschuur 1995a). Small-scale structure in the magnetic field morphology produced by field reversals within the beamwidth of the telescope would not be detected in the Zeeman effect experiment and could especially hide toroidal magnetic fields with small angular scales.

## 3 Discussion: Filaments as Tracers of Current Flow

Our initial study focussed on the nature of the most clearly delineated filament seen in Fig. 3, just to the left and above the map center and partly between the dark areas indicating lack of data. From the appearance of this filament, $\alpha$, it is assumed that is being viewed nearly normal to its axis. Its properties were then derived by examining HI contour maps and observed profiles not shown here. The generally similarity between the dust and gas structures in Figs. 2 and 3 lends support to the notion that "clouds" in the diffuse interstellar medium, which are usually identified with brightness enhancements in HI or 100 $\mu$ area maps, are more likely to be produced by of line–of–sight filament geometry than by simple "cloud" physics. If so, this has far reaching implications for the way such data are interpreted to derive estimates of the physical parameters for interstellar HI. It was in this context that we examined whether plasma physical processes may play a role in controlling the formation and stability of interstellar filaments.

TABLE I

Summary of parameters that produce equality in the Carlqvist Relation.

*Filament $\alpha$ in the H0287+10 region*

| Parameter | Value | Comments |
|---|---|---|
| **Observed** | | |
| HI Column density | $0.85 \times 10^{20}$ | From HI maps at sides of filament |
| Angular width | 0.°2 | Data from two sides of filament |
| Angular rotation | 1.63 km $s^{-1}$ | From HI data |
| Temperature warm, neutral medium | 3000 K | Verschuur and Magnani (1994) |
| Density of warm medium | 0.3 $cm^{-1}$ | For nonplanar directions[1] |
| **Adjustable** | | |
| Aspect ratio | 2 | Takes into account geometry (los through center = 2× los through sides of filament). |
| Distance | 100 pc | Assumed (see text) |
| HI gas temperature | 30 K | Set equal to dust temperature |
| Axial magnetic field in filament | 1.5$\mu$G | From pulsar rotation measures and Zeeman effect data (Verschuur 1995c). |
| Axial magnetic field outside filament | 1.5$\mu$G | Same reference. This is the strength of the general interstellar magnetic field. |
| **Derived** | | |
| Filament $n_H$ | 40.4 $cm^{-3}$ | From HI data and distance |
| Toroidal magnetic field | 5.3 $\mu$G | Produces equilibrium in filament |
| Required current | $1.4 \times 10^{13}$A | From Eq.(1) |

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[1] Reynolds (1983) planar data on the warm ionized medium (8000 K, 0.1 $cm^{-3}$) produces virtually the same pressure.

The philosophy that evolved as the data were examined (with plasma physics concepts in mind) is that HI gas acts as a tracer of the motion and structure of plasma in interstellar space. We will next describe what emerges when the data are considered from this point of view.

Carlqvist and Gahm (1992) first demonstrated that electric currents may generate and maintain interstellar filamentary structure. Key to their discussion is the theory of a generalized Bennett pinch, which involves a cylindrically symmetric plasma filament. A helical magnetic field with a toroidal component $B_\varphi$ and an axial component $B_z$ exists in a filament with radius $a$ inside which a current $I(a)$ flows. The linear density in the filament, $N(a)$, is defined as $\pi a^2 n$, where $n$ is the plasma volume density, which we will take to be the same as the neutral gas volume density, $n_H$. The mean mass of the plasma particles is $m$, which includes neutrals, electrons, ions and a fraction of helium. For these calculations it is taken to be $2 \times 10^{-24}$ gm. The neutral gas is assumed to be coupled to the ionized component (e.g., Kahn and Dyson, 1965).

The generalized Bennett relationship (Carlqvist, 1988) that describes the equilibrium of the filament contains five distinct terms:

$$\mu_0 I^2 (a) + 4\pi G m^2 N^2 (a) = 8\pi \left[\Delta W_k (a) + \Delta W_{Bz} (a) + W_{rot} (a)\right] \tag{1}$$

Peratt (1992) has labelled this the *Carlqvist Relation.* The two terms on the left of Eq. (1) represent the pinching forces due to the current and gravity. A current $I(a)$ in the filament generates a toroidal magnetic field $B_\varphi$ related by

$$B_\varphi (a) = \frac{\mu_0 I (a)}{2\pi a} \tag{2}$$

The terms on the right represent expansive forces, except in the case where the external gas pressure overcomes internal gas pressure in the filament. This follows from the fact that the first term on the right represents the excess kinetic energy in the filament given by

$$\Delta W_k (a) = 2\pi r p_k dr - \pi a^2 p_k (a) \tag{3}$$

where

$$p_k (a) = n_W k T_W$$

is the kinetic pressure in the warm (here taken to be neutral) gas just outside the filament, and

$$p_k = n_H k T_H$$

is the gas pressure inside the filament, whose density and temperature are derived from the HI data. It was found that under certain circumstances, depending mainly on the filament distance chosen (usually an unknown parameter), the external gas pressure can be of the order of, or greater than, the internal gas pressure. Bear in mind that the filament gas density can be derived from the HI observations if the distance to the filament is known. In the analysis described below, it was noted that there is always a critical value for the (unknown) filament distance beyond which the external gas pressure is calculated to be greater than the internal pressure, so that the relative importance of the Bennett pinch in stabilizing the filament appears to be reduced. It may be no more than a coincidence that the critical distance is usually of the order judged to be reasonable for the filaments, and may in fact hint at a new way to obtain this distance.

A second point concerning how to estimate the value of $\Delta W_k (a)$ in Eq.(3) needs to be stressed. The HI in the region in question is clearly morphologically similar to associated cold dust (cirrus). The temperature of dust in atomic filaments is around 30 K (Boulanger and Perault, 1988; Verschuur *et al.*, 1992) yet the observed HI emission linewidths are of order 4 km $s^{-1}$, which corresponds to ~340 K. This disparity between expected gas temperature and observed linewidth has often been noted in the study of interstellar HI and turbulent motions have usually been blamed for the difference. Here we suggest that the HI linewidth is broadened by the presence of rotation around the filament axis, which relates to the last term in Eq. (1).

The excess rotational energy due to angular velocity $\omega$ is given by

$$W_{rot}(a) = \int_0^a 2\pi r \frac{mn\omega^2 r^2}{2} dr \qquad (4)$$

Interstellar HI filaments are barely resolved in most current observations (e.g., Verschuur *et al.*, 1992) so that rotation about their axes could play an important role in defining emission profile linewidths. The amount of rotation in Filament $\alpha$ was determined by comparing profiles observed toward the filament edges; their central velocities are separated by 3.26 km $s^{-1}$. The emission linewidths (~4 km $s^{-1}$) are of this order and it may be possible that line broadening may be produced by rotation around the filament axes of ~2 km $s^{-1}$. For use in Eq. (1), $\omega = v/a$ was derived from the profile data, which imply $v = 1.63$ km $s^{-1}$ for this filament.

The excess magnetic energy term in Eq. (1) is given by

$$\Delta W_{Bz}(a) = \int_0^a 2\pi r \frac{B_z^2}{2\mu_0} dr - \pi a^2 \frac{B_z^2(a)}{2\mu_0} \qquad (5)$$

where $B_z(a)$ is the axial magnetic field just outside the filament.

We next attempt to derive values for the current that would generate a magnetic field to confine the filament. Our analysis using the Carlqvist relationship is slightly different from that offered by Carlqvist and Gahm (1992). They took the filament cold gas temperature to be given by the HI emission linewidth and had no information on filament rotation.

As a first order approach to the data, the above equations were applied using the physical parameters given in Table 1. Eq. (1) was entered into a spreadsheet to allow the various parameters to be adjusted so that their effect on the outcome of the calculations could be readily explored. The finally chosen parameters are indicated in the table and these values are reasonable in the light of present knowledge about conditions in interstellar space (references in table). In particular, the distance of 100 pc is of the order expected for relatively local gas at intermediate galactic latitudes. These parameters listed in Table 1 combine to produce an equality in Eq. (1). The current is estimated to be $1.4 \times 10^{13}$ A which generates a toroidal magnetic field of 5.3 $\mu$G. These values are similar to those found by Carlqvist and Gahm (1992) for an unrelated set of filaments.

TABLE II

Stability of Other Filaments.

| | Region A[1] | Eridanus[2] | |
|---|---|---|---|
| References for data | Verschuur (1974a, 1991a) | Verschuur *et al.* (1992) | |
| Filament diameter | $\sim 0.^\circ 4$ | $\sim 0.^\circ 6$ | |
| Rolling motion | $\sim 5.0$ km $s^{-1}$ $\text{degree}^{-1}$ | $\sim 6$ km $s^{-1}$ $\text{degree}^{-1}$ | |
| Rotation velocity | $\sim 2.5$ km $s^{-1}$ | $\sim 1.8$ km $s^{-1}$ | |
| HI column density, $N_H$ | $1.5 \times 10^{20} \text{cm}^{-2}$ | $3.0 \times 10^{20} \text{cm}^{-2}$ | |
| Distance | 100 pc | 150 pc | 400 pc |
| Implied toroidal magnetic field strength | 7.5 $\mu$G | 6.0 $\mu$G | 3.4 $\mu$G |
| Required current | $3.9 \times 10^{13}$A | $7.1 \times 10^{13}$A | $11.0 \times 10^{13}$A |

[1] Relates to a segment of a highly elongated filament in data presented by Verschuur (1974a), see text.

[2] From Verschuur *et al.* (1992) who discuss the distance estimates, see text.

Substitution into Eq. (1) shows that gravity plays no role in controlling the filament. Most striking is the importance of rotation in determining the magnetic field required to constrain the filament. Varying the rotation velocity from 1–4 km/s changes the required constraining toroidal magnetic field strength from 3.3–12.8 $\mu$G, which in turn requires a current of 0.9–3.4 $\times 10^{13}$ A.

If we insist on an additional constraint, that external gas pressure *not* dominate internal gas pressure, then the distance of the filament has to be $<$140 pc. Otherwise the toroidal magnetic field and external gas pressure will combine to stabilize Filament $\alpha$.

Changing the input parameters (Table 1) revealed that a 20 to 30% unbalance in Eq. (1) to make either external or internal forces dominate is produced by roughly the same percentage change in any of the parameters, except that the equality is least sensitive to the strength of the axial field outside the filament and the temperature and density of the surrounding warm plasma.

Once the relevance of introducing rotation into the Carlqvist relationship was recognized, other data sets, in which this author had previously become aware of possible rotation, were re–examined. For example, notes made during the analysis phase of the work reported by Verschuur (1991a,b) referred to "rolling motion," which implies rotation about a filament axis. Table 2 summarizes an attempt to estimate the parameters characteristic for the regions mapped by Verschuur (1974a). The values of the toroidal magnetic field strength and current along this filament axes, found by applying Eq.

(1), are given. The current is again of the order found by Carlqvist and Gahm (1992).

Another case of rolling motion in filaments was noticed during the study of the structure in Eridanus (Verschuur *et al.*, 1992). This was not mentioned at the time because it did not seem relevant. However, re–examination of the data shows that Filament A exhibits velocity gradients of ∼6 km $s^{-1}$ per degree normal to the filament axis. A similar effect is seen in Filaments B and C. Considering only Filament A, a rotation velocity of 1.8 km $s^{-1}$ for a diameter of 0.°6 is estimated. The parameters relevant to Filament A are shown in Table 2. The derived quantities have been calculated for two possible filament distances discussed by Verschuur *et al.*, (1992). It is found that for the choice of parameters shown in Table 2, the internal gas pressure exceeds that outside the filament if the distance is <210 pc, which means that that if current flow is important in stabilizing this filament it must be at the closer of the two distances considered. Otherwise the pressure term acts to confine the filament in the absence of current flow.

Examination of the data summarized in Tables 1 and 2 suggest that the dominant motion tending to disrupt the filaments may be rotation about their axes. Such rotation results from plasma flowing along the toroidal magnetic fields lines generated by the current which produces the Bennett pinch to stabilize the filament.

## 4 Conclusions

Our analysis suggests confirmation of the model proposed by Carlqvist (1988) and Carlqvist and Gahm (1992), that the physics of the generalized Bennett pinch applies to gaseous interstellar filaments. This has far–reaching implications for the study of the properties of interstellar matter. The role of large-scale currents may be far more important in defining interstellar structure than has generally been recognized within the astronomical community. Diffuse interstellar HI is clearly highly filamentary. In low-resolution surveys, the pervasiveness of filaments may have been overlooked by labelling localized enhancements in HI brightness as "clouds" defined as nearly spherically symmetric, bound entities. It is suggested that unless such features can be proven to have distinct three-dimensional boundaries under the pervasive influence of gravity or magnetism to maintain their morphology, the cloud concept may only apply to unusual structures in star forming regions where gravitationally–bound giant molecular clouds do appear to exist. Exploration of the model invoking current flow in interstellar space suggests that the strength of the toroidal magnetic field surrounding Filament $\alpha$ in the H0827+10 structure is 5 $\mu$G, relatively independent of any parameter other than distance, given a diameter and a column density of gas through the filament. The field strength is insensitive to the value of axial magnetic field strengths inside and outside the filaments, ,which have been assumed equal. The derived toroidal magnetic field strengths lie in the range where it was hoped that 21–cm Zeeman effect observations would be able to detect them. Currently two factors conspire to make such measurements very difficult. Toroidal magnetic fields in barely resolved filaments tend to cancel in the beam and for large angular diameter structures existing radio telescopes suffer from systematic effects that make detection of magnetic fields toward the edge of filaments especially challenging (Verschuur, 1995a,b). Works proceeds on examining available data to test the plasma model of filament creation and stabilization and plans are underway to look more carefully at specific HI features to relate structure to velocity in order to identify the existence of toroidal motion, the signature of the Bennett pinch.

## 5 Acknowledgements

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