THE MAGELLANIC STREAM*

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Abstract. A southern sky survey of H I in the velocity range -340 km s^{-1} to $+380 \text{ km s}^{-1}$ has shown that a long filament of H I extends from the Small Magellanic Cloud (SMC) region down to the South Galactic Pole and connects with the long H I filament discovered recently by Wannier and Wrixon (1972) and van Kuilenburg (1972). There is also some evidence that the feature continues on the other side of the Magellanic Clouds and crosses the galactic plane at $l=306°$. The whole filament, which follows very closely a great circle over its entire 180° length, is given the name 'The Magellanic Stream'. It may have been produced by gravitational interaction between the SMC and the Galaxy during a close passage (20 kpc) of the SMC some 5×10^8 yr ago although it is impossible to account for the observed radial velocities along the Stream unless some force other than gravity is invoked to act on the Stream as well.

Recently a southern sky survey has been made for H I in the velocity range -340 km s^{-1} to $+380 \text{ km s}^{-1}$ using the 18-m reflector at Parkes. This survey has revealed (Figure 1a) a long filament of H I which extends from the region of the Small Magellanic Cloud (SMC) to the South Galactic Polar cap and beyond. This is given the name 'The Magellanic Stream'. All H I is plotted in this diagram except the 'zero-velocity' (i.e. local) gas. The average velocity half-width of the H I in the Magellanic Stream is about 30 km s^{-1} which is much broader than the average half-width of 7 km s^{-1} of gas in the local spiral arm.

Figure 1b shows the distribution of H I with high positive velocity (greater than 200 km s^{-1} with respect to the local standard of rest and clearly resolved from spiral arm emission) discovered on the other side of the SMC and extending through the galactic plane at $l=306°$ and up to $b=+30°$ which may also belong to the Magellanic Stream. The two clouds centred on $l=289°$, $b=20°$ and $l=268°$, $b=20°$ were discovered by Wannier *et al.* (1972), although the latter cloud has probably been produced by the expanding shell of the Gum Nebula and should not be included in the Magellanic Stream.

Figure 2 shows the full extent of the Magellanic Stream inked in on an Aitoff projection of the sky in galactic coordinates. The section between $l=320°$, $b=-80°$ and $l=80°$, $b=-65°$ had been surveyed previously by van Kuilenburg (1972); see also Dieter (1965) and Hulsbosch and Raimond (1966). Wannier and Wrixon (1972) used a more sensitive receiver to increase the observed length of this section of the Stream up to $l=90°$, $b=-30°$. The cross-hatched patches are the clouds of high velocity H I discovered much earlier by northern hemisphere observers mostly at positive latitudes in the longitude range 80° to 180°.

A striking feature of the Magellanic Stream is that it follows closely a great circle

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over its entire 180° across the sky. If all the H I in the Stream were at the distance of the SMC (63 kpc), its mass would be about $10^9\ \mathfrak{M}_\odot$ which is equal to the combined mass of H I in the LMC and SMC. The gas mass of the Inter-Cloud region accounts for half of this total.

Figure 3 shows the variation of radial velocity (V_{GSR}) with angular distance (θ) along the Stream using the coordinate system of Wannier and Wrixon (1972) in their Figure 2. The radial velocities referred to the local standard of rest (LSR) have been corrected for the galactic rotation at the Sun. These corrected velocities ($V_{GSR} = V_{LSR} + 225 \sin l \cos b$) are essentially velocities with respect to a non-rotating Galaxy. The systematic variation of radial velocity found by Wannier and Wrixon is seen to continue until the Magellanic Clouds are reached but not beyond them, which produces a nagging doubt as to whether this H I is really part of the Stream.

Many interpretations of the Magellanic Stream have been considered but the most

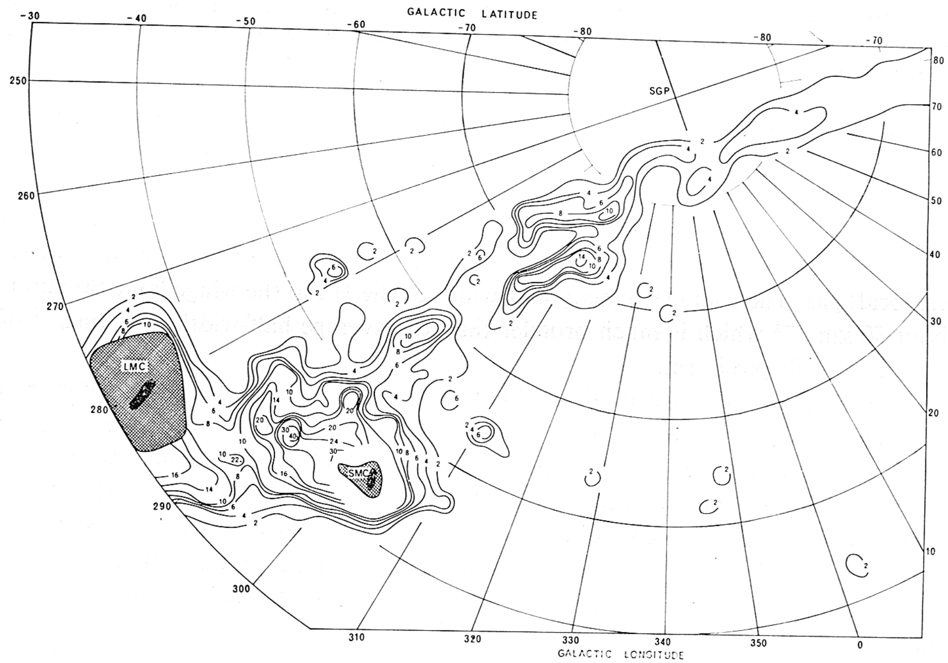

Fig. 1a.

Fig. 1a–b. The contours give the surface densities of the H I in the Magellanic Stream obtained using the 18-m reflector at Parkes. The contour unit is 2×10^{19} atom cm^{-2}. The cross-hatched regions represent the approximate optical extent of the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC).

(a) The section between the Magellanic Clouds and the South Galactic Polar region; all H I within the velocity range -340 km s^{-1} to $+380$ km s^{-1} is plotted except the 'zero-velocity' H I, i.e. local spiral arm gas.

(b) The section between the Magellanic Clouds and $+30°$ galactic latitude; all H I greater than $+200$ km s^{-1} relative to the local standard of rest is plotted. The two clouds centred on $l = 289°$, $b = 20°$ and $l = 268°$, $b = 20°$ were taken from Wannier *et al.* (1972). The latter cloud has probably been produced by the expanding shell of the Gum Nebula and should not be included in the Magellanic Stream.

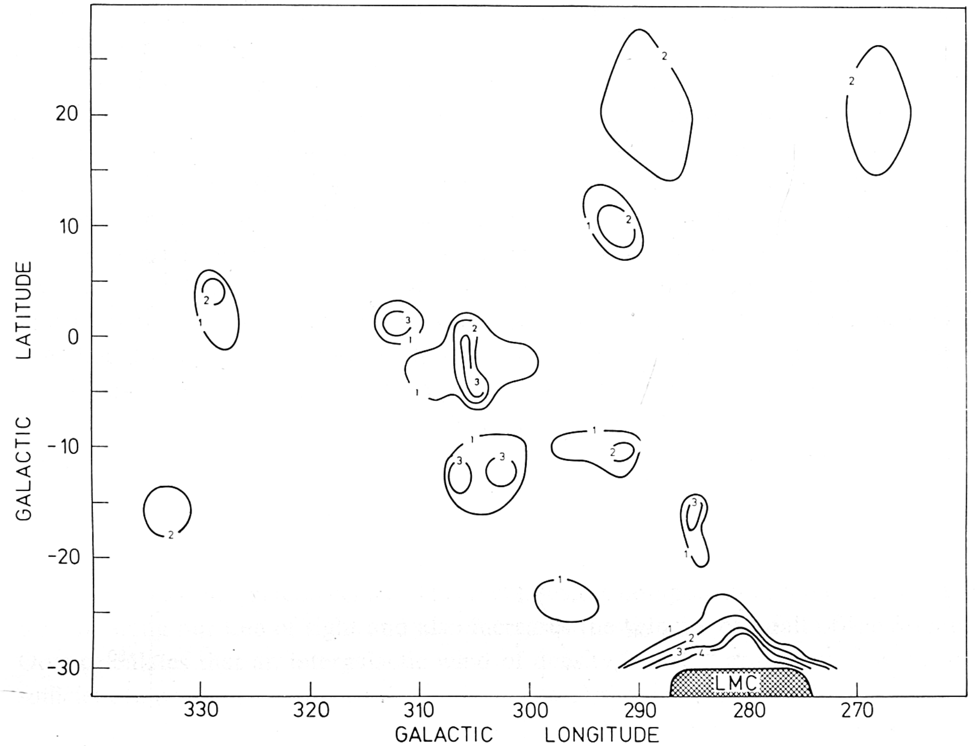

Fig. 1b.

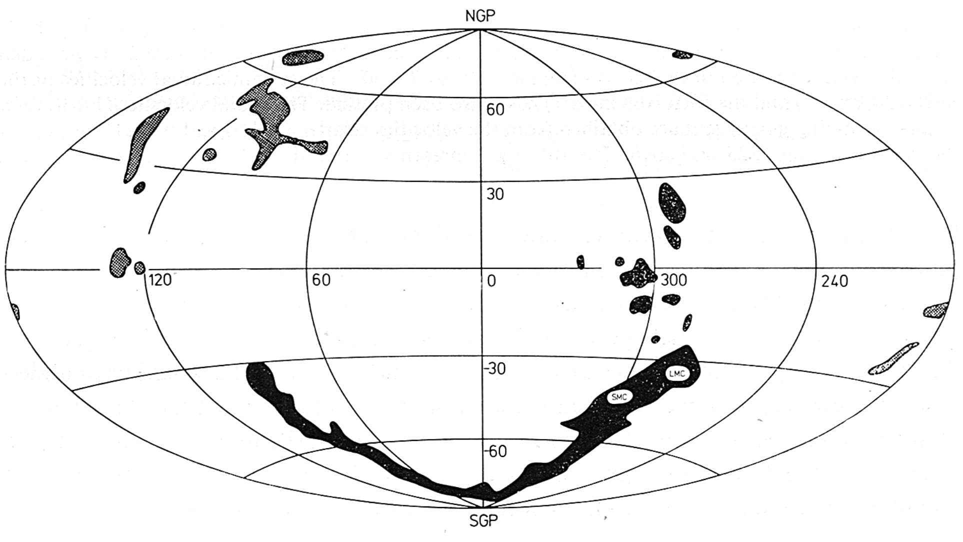

Fig. 2. The Magellanic Stream is inked in on this Aitoff projection in galactic co-ordinates. The cross-hatched areas are the high velocity H I clouds discovered much earlier by northern hemisphere observers (cf. Hulsbosch, 1972).

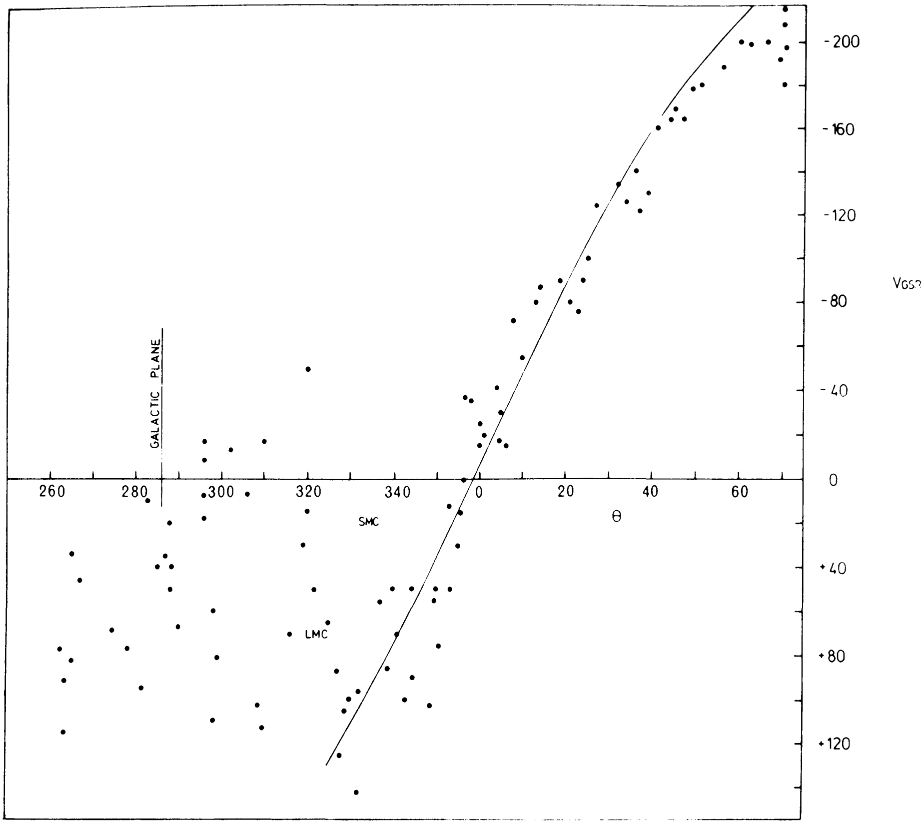

Fig. 3. Plot of radial velocity in km s^{-1} (V_{GSR}) versus the angular distance (θ) along the Magellanic Stream using the co-ordinate system of Wannier and Wrixon (1972) in their Figure 2. Their radial velocities have been used in the section from $\theta = 70°$ to $\theta = 30°$. The systemic radial velocities of the SMC (20 km s^{-1}) and the LMC (68 km s^{-1}) have also been plotted. The radial velocities (V_{GSR}) refer to a non-rotating galaxy and are obtained from the velocities relative to the local standard of rest by the relation $V_{LSR} + 225 \sin l \cos b$. The full line represents the relation $V_{GSR} = -240 \sin (\theta + 2°)$.

favoured one is that gravitational interaction between the SMC and the Galaxy has pulled out the Magellanic Stream from the SMC. Toomre, in unpublished work referred to by Mirabel and Turner (1973), has constructed an orbit for the SMC about the Galaxy in which perigalactic passage occurred some 5×10^8 yr ago at a distance of 20 kpc from the galactic centre. He found that the SMC would have undergone severe disruption, material being drawn out into a bridge and a tail characteristic of such violent tidal events. The tail in his model lay well behind the LMC but projected onto the line joining the two galaxies, and Toomre thought that the Inter-Cloud H I (Hindman *et al.*, 1963; Turner, 1968) may belong to the tail. The bridge lay between the SMC and the Galaxy (see Mirabel and Turner, 1973) but was angled at about 40° to the Magellanic Stream. However, it may be possible to allow the SMC to have a more highly inclined orbit about the Galaxy, which would shift the bridge closer to the South Galactic Pole and more nearly coincident with the Magellanic Stream.

Clutton-Brock (1972) has produced plots to show the tearing of a galaxy by the close passage of a very much larger galaxy. He finds that, under these conditions, the gas and stars are drawn out from the smaller galaxy to form a very prominent bridge and tail. If the orbit of the SMC were highly inclined to the galactic plane then it may be seen from Clutton-Brock's Figures 4g and 4i that in 5×10^8 yr after perigalactic passage, a bridge and tail would be formed by the SMC giving a spatial distribution very similar to that of the Magellanic Stream. Wright (private communication) has made similar computations to those of Clutton-Brock and has reached a similar conclusion.

Although the existence and position of the Magellanic Stream may be explicable in this way, the models do not account for the radial velocities observed along the Stream. In particular the high negative radial velocity ($V_{GSR} = -216$ km s^{-1}) at the tip of the Stream at $l = 90°$, $b = -30°$ is almost an order of magnitude greater than the -30 km s^{-1} predicted by the models of Clutton-Brock and Wright. Oort has suggested (private communication) that this difficulty may be overcome if the Magellanic Stream 'snowploughs' through an intergalactic wind and is thereby braked and blown towards the galactic centre. This increases the component of the velocity of the Stream along our line of sight and also increases the velocity of infall of the Stream. Oort calculates that an intergalactic wind of density 2×10^{-4} atoms cm^{-3} would be sufficient to produce the observed radial velocity at the tip of the Stream, a density of the same order as is necessary to explain the stability of the Local System (Oort, 1970). In addition Oort invokes an intergalactic wind of this density to explain the high velocity H I clouds found by northern hemisphere observers at positive latitudes between longitudes 80° and 180°.

One difficulty with this concept is that denser parts of the Stream, such as that around $l = 300°$, $b = -73°$, would be relatively unaffected by snow-ploughing through the intergalactic wind and would continue along their original orbits. They should then have more positive radial velocities than the nearby, less dense sections whereas the reverse is the case. In addition it is difficult to explain the high positive radial velocities in the Stream near the Magellanic Clouds (e.g. 130 km s^{-1} at $l = 286°$, $b = -47°$ and 90 km s^{-1} at $l = 294°$, $b = -58°$) compared to the systemic radial velocities of 20 km s^{-1} for the SMC and 68 km s^{-1} for the LMC.

It is tempting to speculate that part of the Magellanic Stream may already have hit the galactic plane within 5 kpc of the Sun at $l \approx 100°$ and that its momentum pushed some disk gas to z distances of several kiloparsecs. As the width of the Stream is about 5 to 10 kpc, the disk gas would have been disturbed over a broad range of galactic longitudes around $l = 100°$. At this point the mechanism put forward by Oort (1970) to explain the origin of the high velocity H I clouds (cross-hatched in Figure 2) may operate, so that the gas falls back into the galactic plane under the pressure of the intergalactic wind and the gravitational field of the Galaxy. This action of the Magellanic Stream on the H I in the plane replaces the need for super-explosions postulated by Oort (1970) to replenish the gas in the halo.

The discovery of the Stream suggests many follow-up observations, the most important of which is to search for optical emission. In this regard Bok (1966) commented that a striking feature of the distribution of globular clusters in the Clouds is that many of them are far from the two galaxies, and indeed some cannot be assigned membership specifically to either Cloud (Gascoigne and Lyngå, 1963).

This paper would not be complete without mentioning earlier related work. Nearly twenty years ago de Vaucouleurs (1954) discussed the possibility of a connection between the Magellanic Clouds and the Galaxy and coined the name 'The Magellanic Stream', and Kerr and Sullivan in 1969 considered that the high velocity H I clouds known at that time might be satellites of the Galaxy (perhaps debris scattered around the orbit of the LMC) at distances of the order of 50 kpc. It should also be noted that Hulsbosch (1972), when discussing the long South Polar filament found by van Kuilenburg, and Wannier and Wrixon, suggested that "it may be a tidal arm expelled from the LMC by an encounter with the Galaxy".

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DISCUSSION

Carrick: What mass was used for the LMC in the tidal calculations?

Mathewson: $6 \times 10^9 M_\odot$.

Lewis: Does the Magellanic Stream have any connection with the H I companion of NGC 300 found by Shobbrook and Robinson (*Australian J. Phys.* **20**, 131, 1967) in the region of the South Galactic Pole?

Mathewson: The large cloud of H I found by them near NGC 300 is, in fact, part of the Magellanic Stream.

G. de Vaucouleurs: It is not entirely clear to me that the gaseous stream you observe is the same sort of thing as the streams of stars discussed by Dr Toomre.

Toomre: To a first approximation, all the passengers (gas and stars) ride alike so far as gravity is concerned.

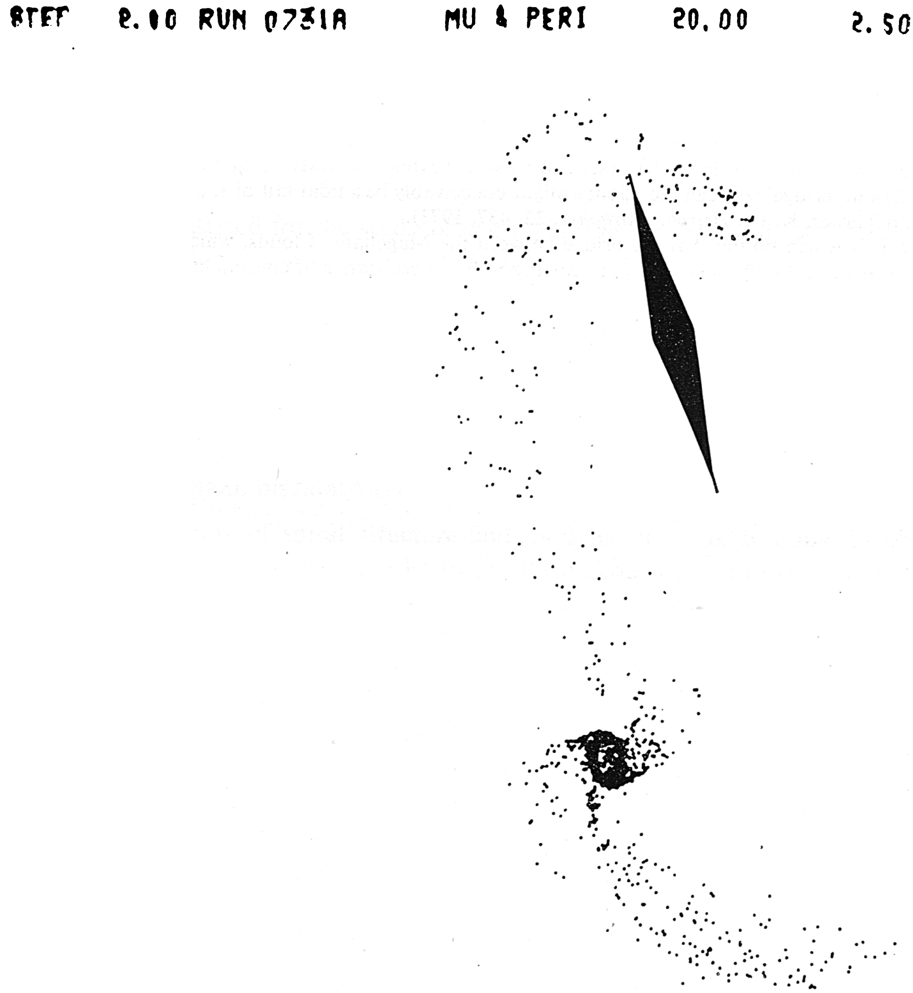
G. de Vaucouleurs: What we see in most of the tails is stars. Why do we see gas in this case but no stars?

Mathewson: They may be there, but we've not yet had time to look for them.

Oort: Unless the gas in the stream is very clumpy, its density must be so low that one cannot expect new stars to be formed.

Mathewson: Some preliminary observations we have made with the Parkes 210-ft dish indicate that the stream does indeed have a clumpy structure.

van den Bergh: If the tidal interaction between the Galaxy and the Clouds was able to detach



Model by Wright (see next page).

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about one-quarter of the neutral hydrogen in the Clouds then it should also have been able to rip off some of the globular clusters.

Mathewson: I agree, and they should be searched for.

Ekers: Detection of the stars or globular clusters torn out with the gas could provide a definitive test of the theory of intergalactic braking, since these old stars will presumably follow the unbraked trajectory and have radial velocities quite different from the gas.

Wright: I have a simple dynamical model (see previous page) for the Galaxy-LMC interaction that does not completely work! The *positional* features agree well with the Mathewson, Cleary, Murray Stream but the *radial velocities* disagree at small Galactic latitudes. Although we must probably look to some resistive mechanism to produce the high negative radial velocities, I believe the stream is basically an inter-active phenomenon.

Oort: What model did you use for the Magellanic Cloud?

Wright: The mass ratios of our Galaxy to the LMC are not critical within the range 5 to 50, nor is the rotation plane of the LMC within $\pm 45°$. Nor even the perigalactic distance within 15 to 30 kpc. However, the model shown had a mass ratio of 20 to 1, a perigalactic distance of 25 kpc and, before the interaction took place, consisted of a cold, rotating disk of stars in circular orbits. The *present* observed velocities in the LMC are not necessarily in disagreement with the present computed velocities.

Toomre: I would like to bet right here and now that if indeed the Magellanic Stream turns out to have a tidal origin, it will be as some sort of bridge-like debris torn from the *Small* Cloud, rather than from the *Large* Cloud as proposed by Dr Wright.

My reasoning, for what it is worth, rests mainly on the need for a plausible *tail* to complement the claimed near-side tidal damage to whichever Cloud was so mistreated by our Galaxy. I know of nothing as yet that could fairly be described as such beyond the LMC, although the possibly misnamed 21-cm 'bridge' between the Clouds might conceivably be a tidal tail of the SMC (cf. Mirabel, I. F. and Turner, K. C.: *Astron. Astrophys.* **22**, 437, 1973).

Kerr: It is worth noting that the bridge between the Magellanic Clouds, which has been known for 20 yr, is known only in gas, except near the SMC where stars and clusters have been found.