Aust. J. Phys., 1990, **43**, 167–77

The Great Attractor—A Cosmic String? *

D. S. Mathewson

Mount Stromlo and Siding Spring Observatories, Australian National University, Private Bag, Woden, A.C.T. 2606, Australia.

Abstract

A brief review is made of the observational work on large-scale streaming motions in the Local Universe. There is considerable controversy as to whether the Great Attractor model of these streaming motions is correct. Preliminary results are presented of a southern sky survey of spiral galaxies to measure their peculiar velocities using the Tully–Fisher relationship. The region of strong peculiar motions has an elongated shape some 80° in angular extent centred roughly on the Great Attractor enclosing the brightest parts of the supergalactic plane. The peculiar velocities reverse in sign at a distance of 4000 km s^{-1} which is conclusive evidence that such a dominant attracting region exists at that distance. However, there is little evidence of galaxies associated with this attracting mass and most galaxies appear to be participating in the streaming motions. The conclusion is that the attractor is largely invisible. It is proposed that a large moving loop of cosmic string is responsible for the peculiar velocities of the galaxies.

1. Introduction

The story of the Great Attractor starts in 1976 when Vera Rubin and her colleagues found anisotropy of the Hubble flow on surprisingly large scales from observations of spiral galaxies (Rubin *et al.* 1976). Shortly after, the cosmic microwave background dipole was discovered (Smoot and Lubin 1979) and interpreted as motion of our Local Group of 600 km s^{-1} towards $l = 269°$, $b = 28°$ (R.A. $10^{h}36^{m}$, Dec. −26°).

Three vigorous pursuits developed: mapping of large scale structure, mapping of the peculiar velocity field of the Local Universe and searching for small scale fluctuations in the cosmic microwave background (CMB). It was hoped that the results would provide strong constraints to the theories of evolution of our early universe, formation of galaxies and large scale structure.

It is generally agreed that galaxies and large scale structure form by one of two mechanisms: (1) gravitational growth of small density perturbations which grew from quantum/thermal fluctuations during inflation, or (2) growth from gravitating 'seeds' produced in the early universe, such as cosmic strings (Turok 1985). The standard $\Omega = 1$, biassed cold dark matter (CDM) universes produce results in the *N*-body simulations that agree well with the observations

* Paper presented at the joint Australia–USSR Workshop on the Early Universe and the Formation of Galaxies held at Mt Stromlo Observatory, 28–29 June 1989.

0004-9506/90/020167$03.00

of large and small scale structure (White *et al.* 1987) but fail to predict the large peculiar velocities observed over such large scales (see Bond 1986). The hot dark matter (HDM) models with cosmic strings are fairly good at producing the large scale structure and can (but not easily) produce the large peculiar velocities (Bertschinger 1988). Cosmic strings can also survive free-streaming and are able to accrete galaxies, thus satisfying the main criticism of HDM models. However, CDM models are more popular because of the exotic nature of cosmic strings.

Matching the difficulties the theoreticians are experiencing in accommodating the large observed peculiar velocities are the difficulties observationalists are having in agreeing with each other's interpretation of the data. Central to this whole issue is the suggestion by Lynden-Bell *et al.* (1988) that a 'Great Attractor' is responsible for most of the peculiar velocities in our Local Universe. Their Great Attractor (GA) is a large mass of $5{\times}10^{16}M_{\odot}$ lying $4350\,\mathrm{km\,s^{-1}}$ away, beyond the Centaurus cluster, and largely responsible for the peculiar motion of the Local Group of $600\,\mathrm{km\,s^{-1}}$ which produces the CMB dipole. According to CDM models, such a mass is extremely unlikely to exist above our horizon. However, there exists controversy amongst astronomers as to the existence of the GA which is illustrated by the following brief review of the more important papers in this field.

2. Review of the Results of Observations of Peculiar Motions

Aaronson *et al.* (1986), using the Tully–Fisher relation, measured the distance to ten clusters in the distance interval $4000 < V < 11000\,\mathrm{km\,s^{-1}}$. The clusters were distributed around the sky between 0° and 36° declination, the region accessible to the Arecibo radiotelescope. They concluded that they had detected the motion of the Local Group giving rise to the CMB dipole. This consists of two components, Local Group motion towards Virgo and bulk Local Supercluster motion towards Hydra–Centaurus. Essentially they found that their ten clusters were at rest with respect to the CMB and Hydra–Centaurus was the cause of the Local Group's motion.

Dressler *et al.* (1987) arrived at a completely different conclusion as the result of distance measurements of 400 ellipticals with $V < 6000\,\mathrm{km\,s^{-1}}$. The model which fitted their data best was bulk motion of galaxies (including the Local Group) of amplitude $600\,\mathrm{km\,s^{-1}}$ with respect to the CMB in the direction of Centaurus over scales of $10\,000\,\mathrm{km\,s^{-1}}$. They concluded that the motion of the Local Group which produces the CMB dipole is not primarily the result of gravitational acceleration by local, $V < 5000\,\mathrm{km\,s^{-1}}$, mass concentrations.

Lynden-Bell *et al.* (1988) reinterpreted the same data sample as Dressler *et al.* (1987) as large scale flow towards a 'Great Attractor' centred at $l = 307°$, $b = 9°$ (R.A. $13^{\mathrm{h}}15^{\mathrm{m}}$, Dec. −53°) at a distance of $4350\,\mathrm{km\,s^{-1}}$ and mass $5{\times}10^{16}M_{\odot}$. In the far field away from Centaurus, they found no streaming and everything is at rest with respect to the CMB in agreement with Aaronson *et al.* (1986). It is worthwhile noting that the Centaurus clusters which are in the immediate foreground of the GA have peculiar motions greater than $1000\,\mathrm{km\,s^{-1}}$ toward it.

However, Lucey and Carter (1988) from measurements of elliptical galaxies in five southern clusters ($2800 < V < 8800\,\mathrm{km\,s^{-1}}$) do not support the idea of a

GA. They found their clusters at rest with respect to the CMB, apart from one small cluster in Centaurus that is infalling into the largest Centaurus cluster. They believe that the Hydra–Centaurus clusters are the major attractors in this region. Omitting the Centaurus clusters, Lucey and Carter combined their data with Aaronson *et al.* (1986) and Lynden-Bell *et al.* (1988) and derived a motion for the Local Group with respect to the frame of distant clusters that is in good agreement with that inferred from the CMB dipole.

Aaronson *et al.* (1989) measured six clusters in Hydra–Centaurus in the velocity range 2900 to 4600 $\mathrm{km\,s^{-1}}$, disagreeing with Lucey and Carter. They believe that the Local Group and Hydra–Centaurus are moving toward a mass concentration beyond Centaurus at a distance of 4000 $\mathrm{km\,s^{-1}}$. They support the concept of the GA.

Staveley-Smith and Davies (1989) surveyed 290 spirals out to 5000 $\mathrm{km\,s^{-1}}$ and concluded that there is a large attractor in the Centaurus cluster itself at a distance of 3400 $\mathrm{km\,s^{-1}}$. This has the dominant effect on the flow pattern. However, they point out that the dynamical mass of the Centaurus cluster is insufficient to provide the dominant gravitational field by more than an order of magnitude.

To summarise, the observations and their interpretation present a very confused picture; but there is one thing clear—there is something in the direction of Centaurus which is the main perturber of the Hubble flow in our neighbourhood and the CMB dipole points roughly in this direction.

3. Optical and IRAS Dipoles

Alternative techniques such as the determination of the optical and IRAS dipoles for mapping the peculiar velocity field do not necessarily support the GA model. The methods rely on the assumption that light traces mass and that both gravity and light fall off as the distance-squared. The locally measured flux of extragalactic light should then determine the gravity field. Lynden-Bell and Lahav (1989) measured the flux of this light using the Uppsala General Catalogue and ESO–Uppsala Catalogue. Their optical dipole points roughly in the direction of the CMB dipole but a large fraction of the gravity field arises in galaxies at about 2000 $\mathrm{km\,s^{-1}}$ and very little at the distance of the GA.

Yahil (1989) mapped the density structure of the Local Universe using a redshift survey of the IRAS galaxies. He found that the peculiar gravitational field is dominated by the Perseus–Pisces Supercluster followed by a somewhat weaker field at the position of the GA. The field bifurcates at the position of the Local Group which is situated nearly half-way between Perseus–Pisces and the GA (see Fig. 10*b*, Yahil 1989).

4. Southern Sky Survey of Spiral Galaxies

In an effort to resolve this dilemma, a southern sky survey of spiral galaxies was commenced in September 1987 by D. S. Mathewson, V. L. Ford and A. Savage to measure their peculiar velocities using the Tully–Fisher relationship. Five Ph.D. students at Mt Stromlo Observatory, M. Buchhorn, C. Grillmair, E. Vassiliadis, A. Samuel and S. Ryder, each worked for four months on the project as part of their first-year program. The galaxies were selected from the ESO–Uppsala Catalogue of type Sb to Sd, diameters $\geq 1 \cdot 7$ arcmin, velocities $<7000\ \mathrm{km\,s^{-1}}$, inclinations $>40°$ and galactic latitude $>|10°|$.

Rotation velocities were measured either using long slit Hα spectroscopy with the dual-beam-spectrograph on the 2·3-m telescope at Siding Spring Observatory or HI spectroscopy with the 64-m radiotelescope of CSIRO at Parkes. The Cousins I-band surface photometry was carried out using a CCD on the 1-m telescope at Siding Spring Observatory. The GASP software package written by Mike Cawson (see Davis *et al.* 1985) was used to measure the integrated light down to a level of $I = 23 \cdot 5$ mag arcsec^{-2}. The ellipse fitting routine allowed an accurate determination of the inclination which increased the accuracy of measurement of the rotation velocity.

All usual corrections to the data have been made—internal and external extinction, relativistic and Malmquist bias. The 'zero-velocity' HI was observed in the direction of each galaxy and used to measure the extinction in our Galaxy (Burstein and Heiles 1984). All velocities were measured with respect to the frame defined by the CMB. The Fornax cluster was used to calibrate the Tully–Fisher relation assuming a distance modulus of 31·01 (Aaronson *et al.* 1981). This gives a Hubble constant of $84\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$. The relation obtained was $M_{\mathrm{I}} = -7 \cdot 98 \log \Delta V - 3 \cdot 01$ with a scatter of 0·15 mag.; ΔV is the velocity of rotation of the galaxy.

5. Preliminary Results of the Southern Survey

The survey should be completed in January 1990 but some preliminary results are reported here. Three regions were selected: (1) $l = 250°$ to $330°$, $b = 10°$ to $40°$, which contains the Hydra–Centaurus supercluster and the GA; (2) $l = 280°$ to $20°$, $b = -10°$ to $-50°$, which contains the Pavo–Indus clusters; and (3) $l = 220°$ to $40°$, $b = -50°$ to $-90°$ and $l = 230°$ to $270°$, $b = -10°$ to $-50°$, which was chosen to be the control region as it is a region of quiet Hubble flow mostly at large angles to the densest parts of the supergalactic plane and the GA. Region 1 has been fully sampled but Regions 2 and 3 are not yet complete.

The two areas of large peculiar velocities are outlined in Fig. 1 which was taken from the ESO–Uppsala Catalogue of galaxies (Lauberts 1982). They contain the Centaurus, IC 4329 and the Pavo clusters. It appears likely that these two areas are joined across the 'zone of avoidance' caused by the Milky Way. If so, the large radial peculiar velocities occur predominantly in a very elongated regon some 80° in angular extent which is the brightest section of the supergalactic plane.

Figs 2 and 3 plot the peculiar velocities of the galaxies against their distance in $\mathrm{km\,s^{-1}}$ in the zones of strong streaming, $l = 292°$ to $310°$, $b = 10°$ to $40°$ in Region 1 and $l = 310°$ to $0°$, $b = -10°$ to $-45°$ in Region 2 respectively. Fig. 4 plots the peculiar velocities in Region 3, the control zone and shows the scatter to be expected in the measurement of peculiar velocities.

The most important feature of Figs 2 and 3 is that the peculiar velocities reverse sign at about $4000\ \mathrm{km\,s^{-1}}$. On either side of this reversal point, they reach values of around $1000\text{–}1500\ \mathrm{km\,s^{-1}}$. This detection of the 'fall-back' of galaxies beyond the distance of the GA confirms that it exists although

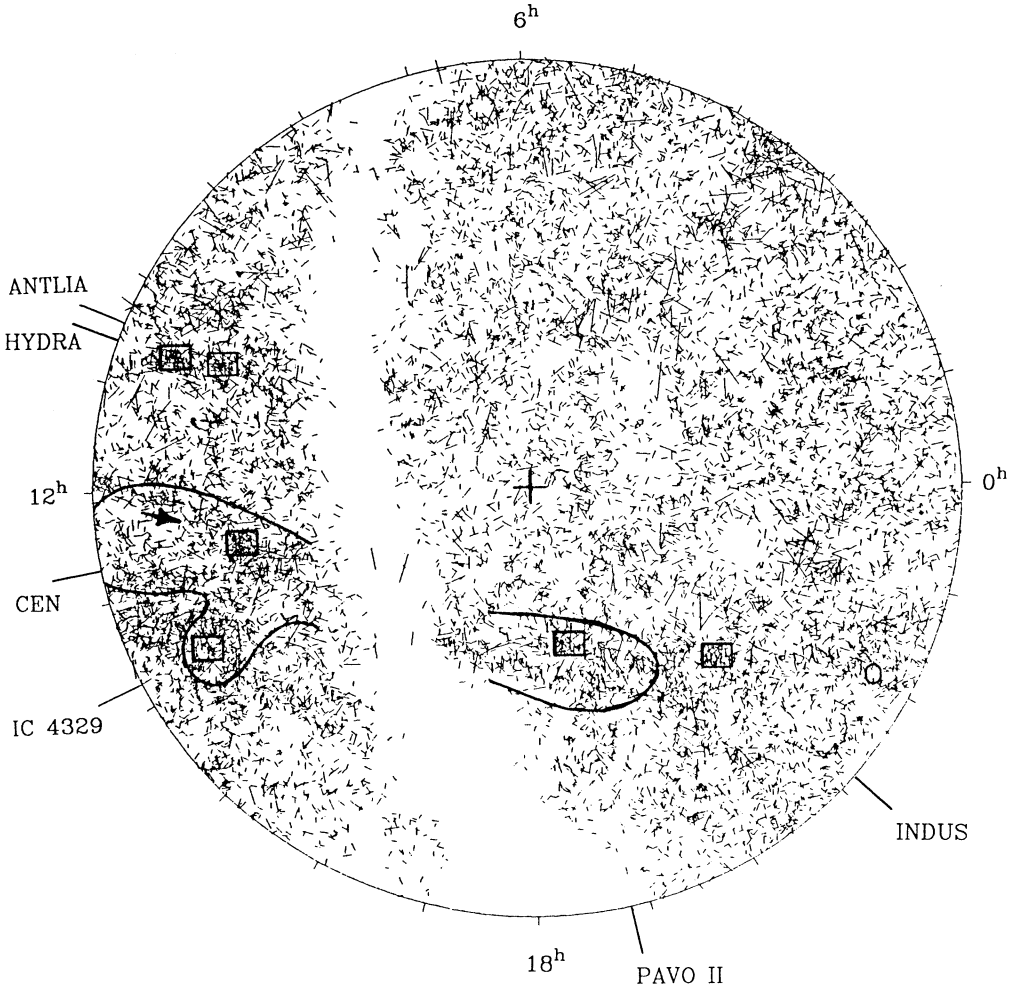

Fig. 1. The two areas where large peculiar velocities are found are outlined on this plot showing the distribution of galaxies south of Dec. $-17 \cdot 5°$ taken from the ESO–Uppsala Catalogue (Lauberts 1982). The projection is in polar coordinates, R.A. 0^h to 24^h, Dec. $-90°$ at the centre. The galaxies are plotted as thin bars having lengths proportional to the major diameter and inclinations according to the position angle. The more prominent clusters are marked. The 'zone of avoidance' caused by the Milky Way is the empty band running vertically left of centre. The arrowhead marks the position at which the loop of cosmic string was laid down and the direction of its motion. The 'O' marks (at lower right) the present position of the loop.

it is cylindrical in shape rather than a spherical mass as in the model of Lynden-Bell *et al.* (1988).

However it is puzzling that neither Fig. 2 nor Fig. 3 gives any indication of galaxies which could be identified with the attracting mass itself at a distance of 4000 km s^{-1}. Most galaxies appear to be participating in the streaming. This is reinforced by the histogram in Fig. 5 of the number of galaxies as a function of their Hubble velocity in Region 1 which has been fully sampled.

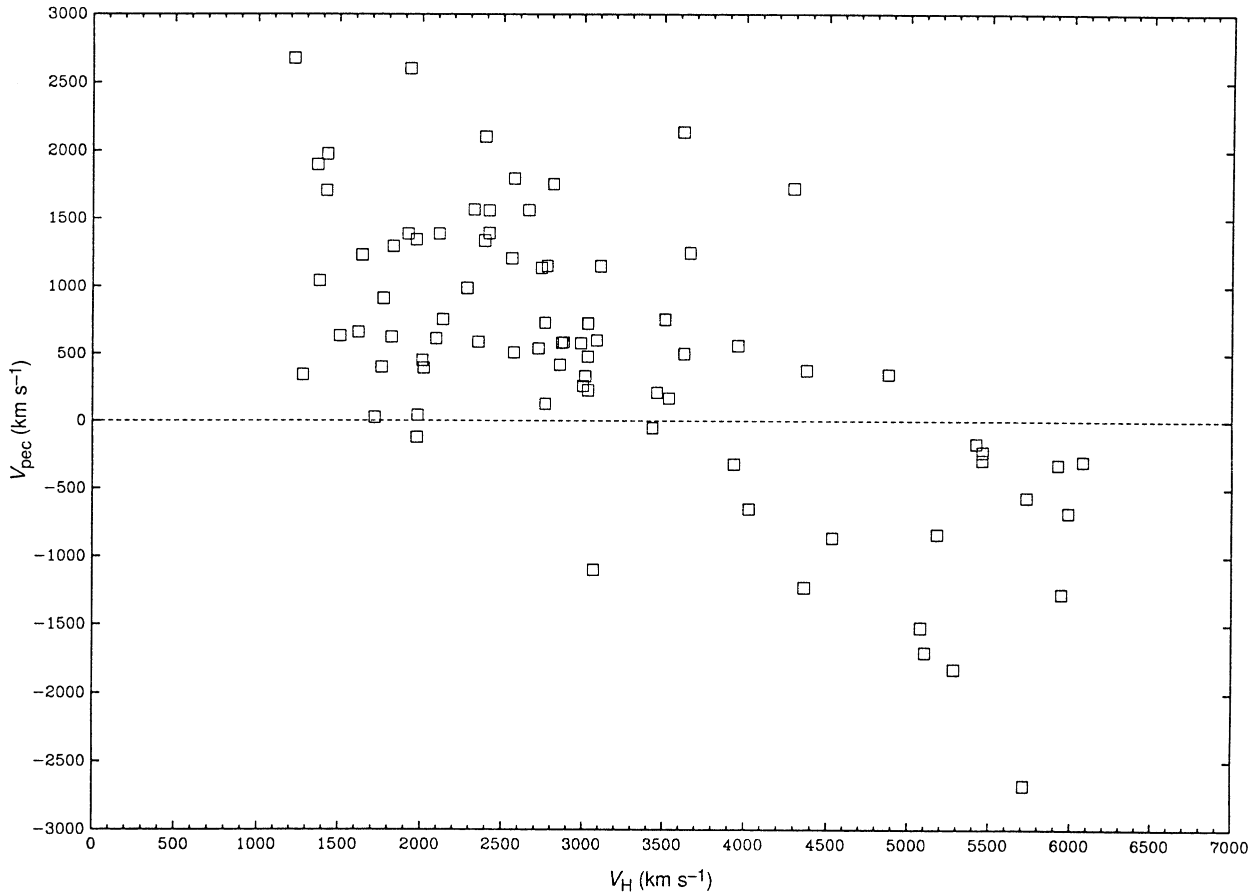

Fig. 2. Peculiar velocities of the galaxies as a function of V_H, their Hubble velocity (distance in km s^{-1}), in the area of strong streaming motions, $l = 292°$ to $310°$, $b = 10°$ to $40°$ in Region 1. This area contains the Centaurus and IC 4329 clusters (see Fig. 1).

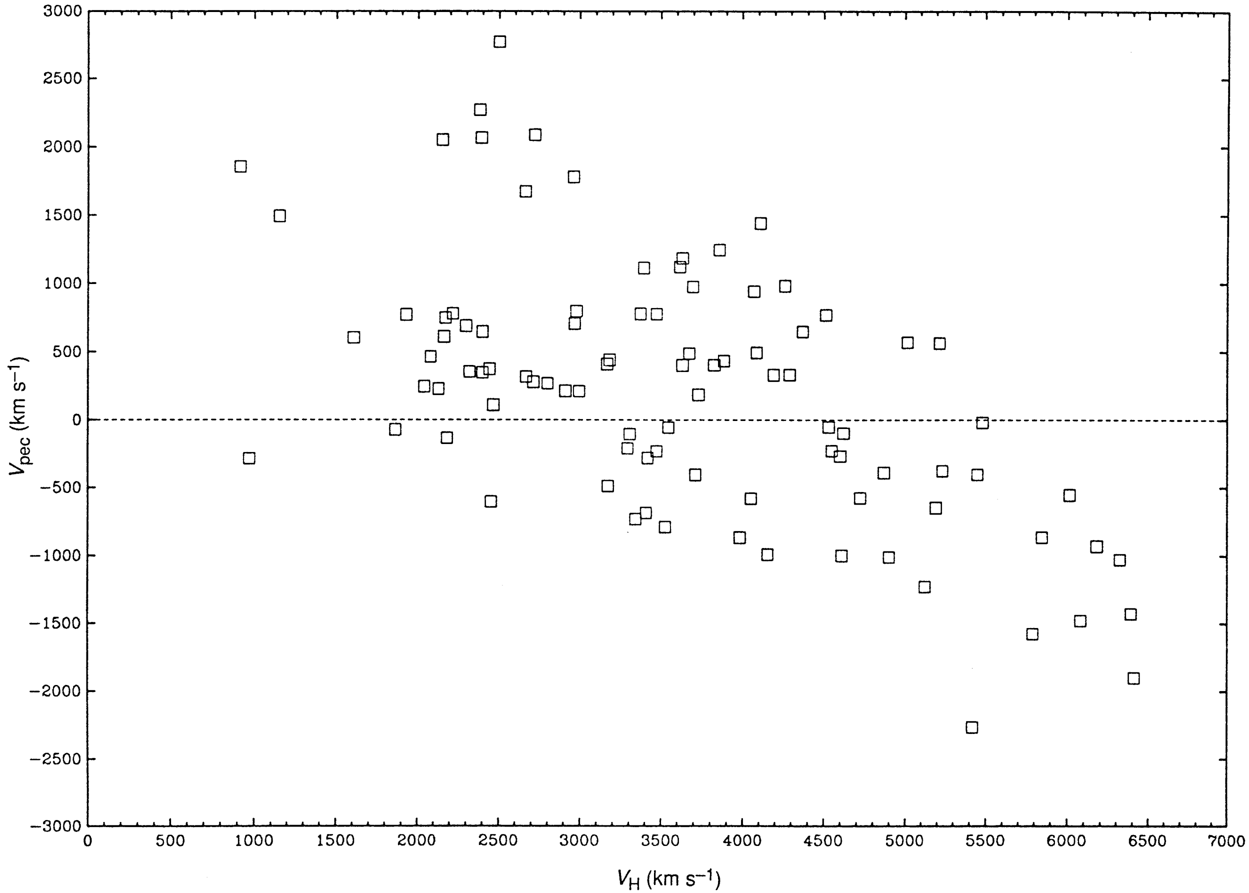

Fig. 3. Peculiar velocities of the galaxies as a function of V_H, their Hubble velocity (distance in km s^{-1}), in the area of strong streaming motions, $l = 310°$ to $0°$, $b = -10°$ to $-45°$ in Region 2. This area contains the Pavo II cluster (see Fig. 1).

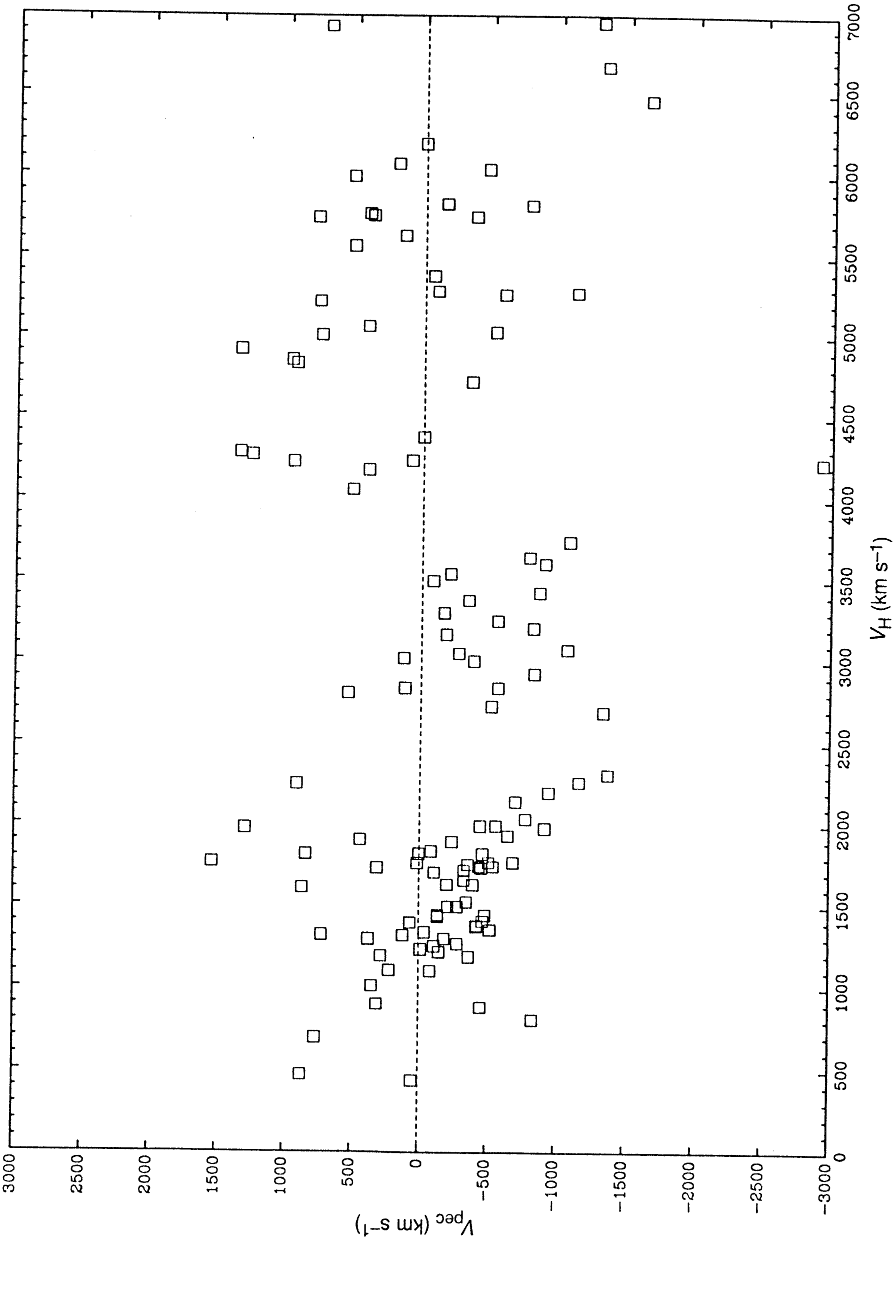

Fig. 4. Peculiar velocities of the galaxies as a function of their distance in km s^{-1} in Region 3, the area of quiet Hubble flow, showing the scatter to be expected in the measurement of the peculiar velocities.

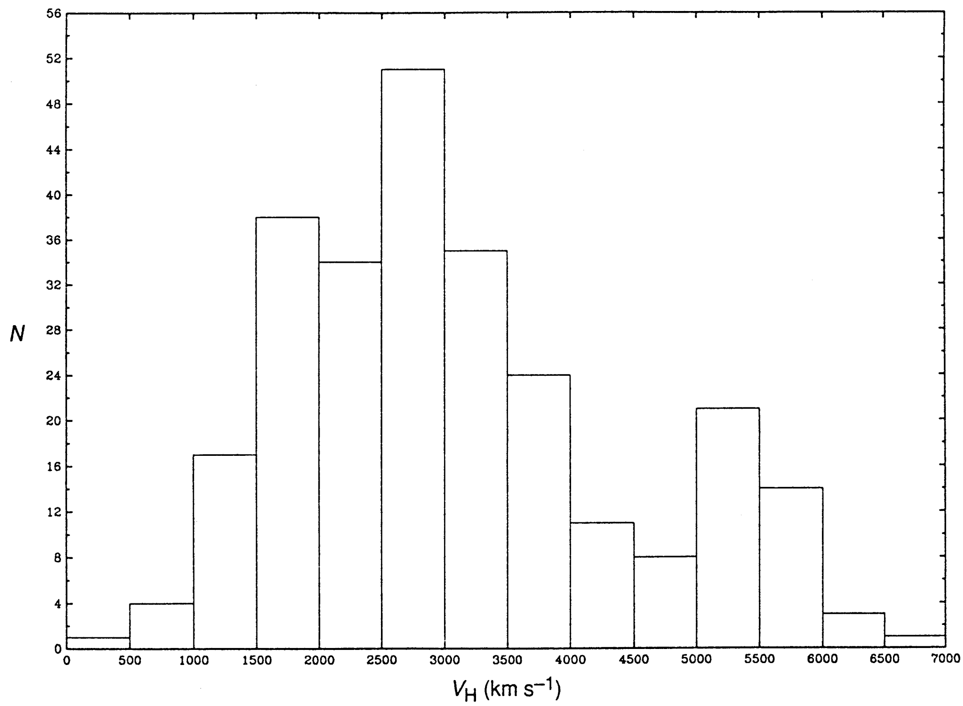

Fig. 5. Number of galaxies as a function of V_H, their Hubble velocity, in Region 1.

This shows the concentration of foreground galaxies around 3000 km s^{-1} but few at 4000 km s^{-1}, the velocity of the attracting mass. The conclusion is that this mass is largely invisible.

6. Cosmic String Loops

What then is the object that has seeded this gravitational collapse? It is unlikely to be dark matter as concentrations of this size and mass would have been detected as fluctuations in the CMB. However, a moving large loop of cosmic string is a possibility, albeit an exotic possibility. [For a review of the properties of cosmic strings see Vilenkin (1985).] Hoffman and Zurek (1988) have already successfully modelled the streaming of galaxies towards the GA induced by a moving loop of cosmic string. However, their model needs to be revised in light of the present results. A better fit can be obtained if the loop moves perpendicular to the line of sight to the GA rather than along the line of sight (see Fig. 1*a* of Hoffman and Zurek 1988). Following their procedure, the loop would have a radius of 300 kpc, a mass of approximately $10^{14} M_{\odot}$ and would be laid down at $z = 100$ with a velocity of $0 \cdot 3c$. The dimensionless string tension $G\mu/c^2$ is about 3×10^{-6}.

A shell of dark matter which was concentric with the loop at that epoch would now have a radius of 40 Mpc and a present day infall velocity relative to the CMB of 500 km s^{-1}. The Local Group would be almost on its perimeter. Inside this shell, the velocity field falls off as r^{-1}, where r is the distance from its centre. This persists in much of the wake of the string loop in accord with the observations (Brandenberger *et al.* 1987; Bertschinger 1988).

At an initial velocity of $v = 0 \cdot 3c$, the isodensity contours of the accretion wake assume a trumpet-like shape (see Fig. 1*c* of Hoffman and Zurek 1988). The bell of the trumpet which coincides with the broadening of the supergalactic plane around the Centaurus cluster is the region where the loop was formed (see Fig. 1). The throat which extends into the Pavo–Indus region, narrows in the direction of its motion.

The present position of the loop is around $l = 30°$, $b = -53°$ (R.A. 22^h05^m, Dec. $-23°$) and lies outside the region of streaming motions (see Fig. 1). It subtends an angle of 40 arcmin and has a velocity of about 900 km s^{-1}. The loop has moved a distance of some 110 Mpc from its starting point near $l = 293°$, $b = 30°$ (R.A. 12^h08^m, Dec. $-32°$). The total mass now collapsing in its accretion wake is approximately $10^{16} M_{\odot}$. The centre of attraction is around $l = 315°$, $b = 5°$ (R.A. 14^h15^m, Dec. $-56°$). This modelling is still in progress and the detailed results will be given in Mathewson *et al.* (1990).

The cosmic string loop should be detectable by its gravitational lensing of more distant galaxies (Cowie and Hu 1987; Hogan and Narayan 1984). A search is underway of SERC Schmidt Sky Survey plates for background galaxies with sharp edges or double images separated by the deficit angle of $8\pi G\mu/c^2 \sim 15$ arcsec.

Hoffman and Zurek (1988) showed that while these large loops are rare, there is about a 1% probability of finding a sufficiently large loop as close as the GA. This is a much more likely event than finding a sufficiently large density peak in the biassed CDM model (Bond 1986). In addition such a large density peak in the CDM would generate a velocity field with a much steeper dependence (r^{-3}) on distance from the peak than that observed ($\sim r^{-1}$) for the GA flow field.

Acknowledgments

I thank the staff of Mt Stromlo and Siding Spring Observatories and of the Parkes Observatory, CSIRO, for maintaining the telescopes and equipment in perfect order throughout the observations; also, the Division of Radiophysics, CSIRO, for giving us such generous allocations of time on the 64-m telescope for this program.

References

Aaronson, M., Bothun, G. D., Cornell, M. E., Dawe, J. A., Dickens, R. J., Hall, P. J., Han Ming Sheng, Huchra, J. P., Lucey, J. R., Mould, J. R., Murray, J. D., Schommer, R. A., and Wright, A. E. (1989). *Astrophys. J.* **338**, 645.

Aaronson, M., Bothun, G. D., Mould, J. R., Huchra, J., Schrommer, R., and Cornell, M. (1986). *Astrophys. J.* **302**, 536.

Aaronson, M., Dawe, J. A., Dickens, R. J., Mould, J. R., and Murray, J. D. (1981). *Mon. Not. R. Astron. Soc.* **195**, 1P.

Bertschinger, E. (1988). *Astrophys. J.* **324**, 5.

Bond, J. R. (1986). *In* 'Galaxy Distances and Deviations from Universal Hubble Expansion' (Eds B. F. Madore and R. B. Tully), p. 255 (Reidel: Dordrecht).

Brandenberger, R., Kaiser, N., Shellard, E. P. S., and Turok, N. (1987). *Phys. Rev.* D **36**, 335.

Burstein, D., and Heiles, C. (1984). *Astrophys. J. Suppl.* **54**, 33.

Cowie, L. L., and Hu, E. M. (1987). *Astrophys. J.* **318**, L33.
Davis, L. E., Cawson, M., Davies, R. L., and Illingworth, G. (1985). *Astron. J.* **90**, 169.
Dressler, A., Faber, S. M., Burstein, D., Davies, R. L., Lynden-Bell, D., Terlevich, R., and Wegner, G. (1987). *Astrophys. J. Lett.* **313**, L37.
Hoffman, Y., and Zurek, W. H. (1988). *Nature* **333**, 46.
Hogan, C., and Narayan, R. (1984). *Mon. Not. R. Astron. Soc.* **211**, 575.
Lauberts, A. (1982). The ESO/Uppsala Survey of the ESO(B) Atlas, European Southern Observatory.
Lucey, J. R., and Carter, D. (1988). *Mon. Not. R. Astron. Soc.* **235**, 1177.
Lynden-Bell, D., Faber, S. M., Burstein, D., Davies, R. L., Dressler, A., Terlevich, R., and Wegner, G. (1988). *Astrophys. J.* **326**, 19.
Lynden-Bell, D., and Lahav, O. (1989). *In* 'Large Scale Motions in the Universe' (Eds V. C. Rubin and G. Coyne), p. 199 (Princeton Univ. Press).
Mathewson, D. S., Ford, V. L., Buchhorn, M., Grillmair, C., Vassiliadis, E., Samuel, A., Ryder, S., and Savage, A. (1990). (in preparation).
Rubin, V. C., Thonnard, N., Ford, W. K., and Roberts, M. S. (1976). *Astron. J.* **81**, 719.
Smoot, G., and Lubin, P. M., (1979). *Astrophys. J. Lett.* **234**, L83.
Staveley-Smith, L., and Davies, R. D. (1989). *Mon. Not. R. Astron. Soc.* **241**, 787.
Turok, N. (1985). *Phys. Rev. Lett.* **55**, 1801.
Vilenkin, A. (1985). *Phys. Rep.* **121**, 263.
White, S. D. M., Frenk, C. S., Davis, M., and Efstathiou, G. (1987). *Astrophys. J.* **313**, 505.
Yahil, A. (1988). *In* 'Large Scale Motions in the Universe' (Eds V. C. Rubin and G. Coyne), p. 219 (Princeton Univ. Press).

Manuscript received 2 October, accepted 3 November 1989