26. Manabe, S. & Broccoli, A. J. *Science* **247,** 192–195 (1990).
27. Ruddiman, W. F. & Kutzbach, J. E. *J. geophys. Res.* **94,** 18409–18427 (1989).
28. Kutzbach, J. E., Prell, W. L. & Ruddiman, W. F. *J. Geol.* (in the press).
29. Arthur, M. A. in *Advisory Panel Report on Earth System History* 51–74 (NSF, Division of Ocean Studies, 1991).
30. Berger, A. L. *Quat. Res.* **9,** 139–167 (1978).
31. Berger, A. & Loutre, M. F. *Quat. Sci. Rev.* **10,** 297–317 (1991).
32. Prentice, M. L. & Matthews, R. K. *J. geophys. Res.* **96,** 6811–6827 (1991).
33. Molnar, P. & England, P. *Nature* **346,** 29–34 (1990).
34. Raymo, M. & Molnar, P. in *AGU 1991 Fall Mtg Prog. Abstr., Eos* **257** Suppl. (Am. Geophys. Un., Washington DC, 1991).
35. Harrison, T. M., Copeland, P., Kidd, W. S. F. & An Yin. *Science* **255,** 1663–1670 (1992).
36. Quade, J., Cerling, T. E. & Bowman, J. R. *Nature* **342,** 163–166 (1989).
37. Raymo, M. E. & Ruddiman, W. F. *Nature* **359,** 117–122 (1992).
38. Prell, W. L., Murray, D. W., Clemens, S. C. & Anderson, D. M. in *The Indian Ocean: A Synthesis of Results from the Ocean Drilling Program Geophys. Monogr.* 70 (eds Duncan, R. A., Rea, D. K., Kidd, R. B., von Rad, V. & Weissel, J. K.) (Am. geophys. Un., Washington DC, in the press).
39. Kroon, D., Steens, T. & Troelstra, S. R. in *Proc. ODP Scient. Res.* **117** (eds Prell, W. L. *et al.*) 257–263 (Ocean Drilling Project, College Station, Texas, 1991).
40. Nigrini, C. in *Proc. ODP Scient. Res.* **117** (eds Prell, W. L. *et al.*) 89–126 (Ocean Drilling Program, College Station, Texas, 1991).

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Magnetic fields as an alternative explanation for the rotation curves of spiral galaxies

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THE flat rotation curves of spiral galaxies are usually regarded as the most convincing evidence for dark matter. The assumption that gravity alone is responsible for the motion of gas beyond the visible disks of galaxies leads directly to the conclusion that there must be perhaps 10 times as much dark matter as visible matter. Other forces besides gravity are usually neglected, as order-of-magnitude arguments seem to suggest they cannot be important. The existence of dark matter is, however, so important an issue that we believe it is wise to consider other possibilities. Here we argue that an azimuthal magnetic field can carry slightly ionized gas with the general galactic rotation, rendering dark matter unnecessary (a related idea was first proposed by Nelson[1]). For the illustrative case of M31, a magnetic field of 6 μG is required, and the synchrotron emission of relativistic electrons in this field is compatible with the observations.

The outermost regions of disc galaxies are observed by means of their gas content; in particular the rotation curve is obtained from the Doppler shift of the 21-cm line of interstellar atomic hydrogen. This gas is sufficiently ionized for magnetic field lines to be frozen in. Magnetic forces therefore influence the motion and distribution of the observed atomic hydrogen. Here we will investigate whether this influence is large enough. The basic assumption behind our equations is that magnetic tension holds the gas together, forcing it to spin faster than pure gravitation would.

Magnetic fields noticeably affect the behaviour of the peripheries of galaxies. Intergalactic magnetic fields may produce a warping of the disc[2,3], corrugations[4] or enhanced ellipticity of the outermost isophotes[5]. Interstellar magnetic fields may have a considerable influence on galactic evolution[6], and in particular may be essential to maintain external rings[7,8]. Here we follow refs 7 and 8 in introducing the equations that will be used in our calculations.

The large-scale structure of the magnetic field may be either 'circular' (pure azimuthal field), or a structure with field lines open to space[9]. In either case the azimuthal component of the magnetic field is large, so only the effect of this component is considered here. We adopt the equations proposed in ref. 7 with one important modification. It was considered there that the stellar and the gaseous systems corotate. This condition must now be removed. For stars in the outermost disc the gravitational and centrifugal forces are in balance. This cannot be assumed for the gas: in the absence of dark matter, the gravitational forces are due to stars, but gas and stars do not corotate. In the outermost disc, stars are not observed, and we may assume that the stellar rotation curve is keplerian. The rotation curve of the gas, however, remains flat, and we do not assume keplerian rotation.

The radial component of the motion equation simply becomes

$$\rho\left[-\frac{\partial V}{\partial r}+\frac{v^2}{r}\right]-\frac{\partial p}{\partial r}-\frac{1}{8\pi r^2}\frac{\partial(r^2B^2)}{\partial r}=0$$

where V is the gravitational potential, v the rotation velocity, p the gas pressure, B the azimuthal magnetic field, ρ the density and r the galactocentric radius.

This equation may be integrated to yield

$$B^2=B_g^2+B_p^2+B_0^2\frac{r_0^2}{r^2}$$

where

$$\frac{B_g^2}{8\pi}=\frac{1}{r^2}\int_{r_0}^{r}\rho\left(v^2\xi-\xi^2\frac{\partial V}{\partial\xi}\right)\mathrm{d}\xi$$

is the contribution of gravity and centrifugal forces to the required magnetic field,

$$\frac{B_p^2}{8\pi}=-\frac{1}{r^2}\int_{r_0}^{r}\xi^2\frac{\partial p}{\partial\xi}\mathrm{d}\xi$$

is the contribution of the pressure gradient force, and the last term represents the influence of the boundary conditions. B_0 is the magnetic strength at the boundary radius r_0, which was taken as 5 kpc. The last term is proportional to r^{-2}, so the results obtained for large radii do not depend very much on the choice

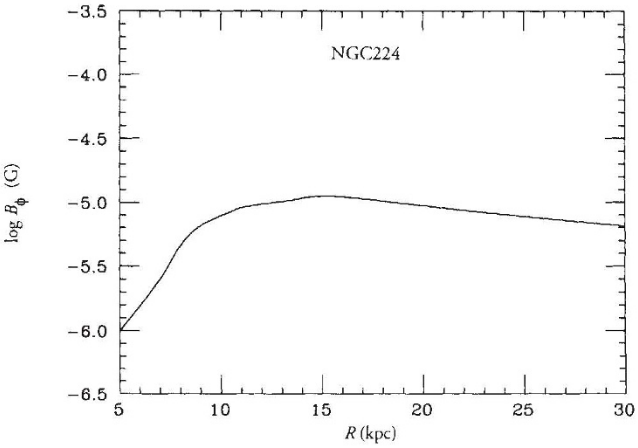

FIG. 1 Azimuthal component of the magnetic field strength in M31.

of B_0 and r_0. Preliminary calculations confirmed this. For $r < 20$ kpc, the adopted densities were the same as in refs 7 and 8, from atomic hydrogen and carbon monoxide data. The densities for $r > 20$ kpc were obtained assuming an exponential disc where the density decreases by one order of magnitude in 10 kpc. The gravitational potential was taken from ref. 10, based on the luminosity profile. The rotation velocities were taken from refs 10 and 11.

The results for magnetic field strength are shown in Fig. 1. For B_0, a value of 10^{-6} G was assumed, as the higher observational values are found in a ring centred at ~10 kpc (ref. 12). This ring was also found in our calculations, although the absolute values were higher and the profile was shifted outwards. The value and slope at 30 kpc are more important for our present purposes. We found $B_0 = 6 \times 10^{-6}$ G and $dB/dr = -2 \times 10^{-7}$ G kpc^{-1}.

For easier comparison with observations[12], we also calculated the synchrotron radiation produced by these magnetic fields and relativistic electrons, following the method of ref. 8. We assumed that the number of relativistic electrons per unit volume and energy interval is proportional to ρ / B, to take into account the energy loss of cosmic electrons due to the synchrotron emission itself (this is based on the model of ref. 13). The constant of proportionality was adopted to match the brightness temperature at 10 kpc. The theoretical profile (Fig. 2) does not agree well with observations for radii less than 10 kpc, but values at small radii depend on boundary conditions, and vertical magnetic fields probably become important. We focus instead on the peripheral results, where the agreement is good. This shows that our values for the magnetic field in the outermost disc are compatible with observations.

To interpret the results better, it is possible to integrate the above equation analytically for large radii, with the following assumptions: the gravitational potential is that created by a point-like galactic mass; the profile of gas rotational velocity is flat; the density and the pressure decrease exponentially. A function $B(r)$ is then easily found. Asymptotically, for radii several times the scale length of the exponential disc, this function is approximated by $B = \text{constant} \times r^{-1}$. This is essentially the B-profile that renders the outer rotation curve flat. The function $B(r)$ plotted in Fig. 1 is fitted by this simple law at large radii.

The obtained magnetic strength is reasonable for the magnetic ring, but could be considered too large at 30 kpc. The stability of the disc with such a strong field and the stability of the field itself pose some problems. Turbulent diffusion and the development of Parker's instabilities in a disc with high magnetic pressure would tend to dissipate the field rapidly. Is some dynamo mechanism enhanced at the rim to compensate these losses? Are 'corrugations', mainly observed in the outer regions of discs[14], a result of enhanced production of Parker's instabilities? In any case, the required magnetic fields are compatible with observations of the radio continuum. Also, these fields must connect with those in the intergalactic medium, which may reach values higher than 10^{-6} G (ref. 15).

We conclude that the flatness of the rotation curve for the outer disc of spiral galaxies, generally presumed to be evidence of dark matter, could instead be the result of interstellar magnetic fields. Direct measurements of these fields by means of the polarized synchrotron radio continuum, at large galactocentric distances, are needed to confirm this interpretation. Magnetic field strengths of ~6×10^{-6} G combined with a slow radial decrease could produce a non-keplerian slope for the rotation velocity. □

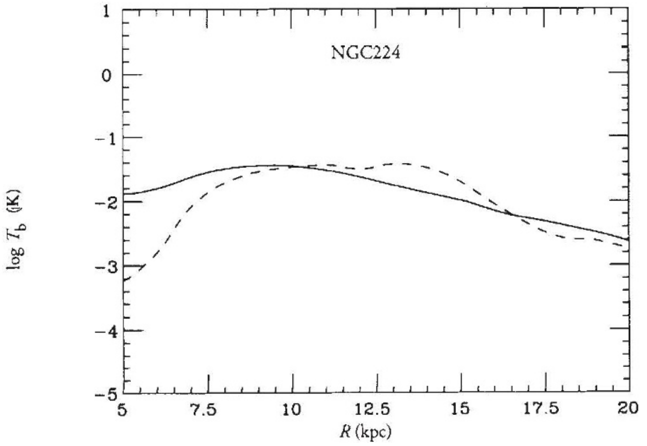

FIG. 2 Brightness temperature profiles for M31. Solid line corresponds to the observational results and dashed lines to this work.

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1. Nelson, A. H. *Mon. Not. R. astr. Soc.* **233,** 115–121 (1988).
2. Battaner, E., Garrido, J. L., Sanchez-Saavedra, M. L. & Florido, E. *Astr. Astrophys.* **251,** 402–410 (1991).
3. Binney, J. *Dynamics of Disc Galaxies* in *Warps* (ed. Sundelius, B.) 297–309 (Göteborgs Univ., Sweden, 1991).
4. Nelson, A. H. & Matsuda, T. *Mon. Not. R. astr. Soc.* **191,** 221–235 (1980).
5. Battaner, E., Florido, E. & Sanchez-Saavedra, M. L. *Astr. Astrophys.* **253,** 89–91 (1992).
6. Beck, R. *Interstellar Magnetic Fields* in *Interstellar Magnetic Fields: Past, Present and Future* (eds Beck, R. & Grave, R.) 2–7 (Springer, Berlin, 1986).
7. Battaner, E. & Sanchez-Saavedra, M. L. *Astrophys. J.* **302,** 450–458 (1986).
8. Battaner, E., Florido, E. & Sanchez-Saavedra, M. L. *Astrophys. J.* **331,** 116–123 (1988).
9. Beck, R. *Magnetic Fields and Extragalactic Objects* in *Interstellar Magnetic Fields in Normal Galaxies* (eds Asseo, E. & Gresillon, D.) 113–128 (Edition de Physique, Cargèse, 1987).
10. Kent, S. M. *Astron. J.* **93,** 816–832 (1986).
11. Newton, K. & Emerson, D. T. *Mon. Not. R. astr. Soc.* **181,** 573–590 (1977).
12. Beck, R. *Astr. Astrophys.* **106,** 121–132 (1982).
13. Lerche, I. & Schlickeiser, R. *Astr. Astrophys.* **116,** 10–26 (1982).
14. Florido, E., Battaner, E., Prieto, M., Mediavilla, E. & Sanchez-Saavedra, M. L. *Mon. Not. R. astr. Soc.* **251,** 193–198 (1991).
15. Vallee, J. P. *Astron. J.* **99,** 459–462 (1990).

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Long-term solar brightness changes estimated from a survey of Sun-like stars

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THE brightness of the Sun varies during the 11-year solar cycle, typically by less than 0.1% (refs 1, 2), and a larger brightness variation is thought to have occurred during the Maunder minimum, from AD 1645 to 1715 (refs 3–5). But because individual solar cycles are different in form, amplitude and length, and because accurate solar data have been available only for the most recent two or three cycles, there is no direct way of understanding long-term solar variability. Here we present a compilation of eight years of observations of 33 Sun-like stars and report year-to-year brightness changes that substantially exceed the analogous solar fluctuations. We have also measured chromospheric magnetic activity in these stars and find that it correlates with the brightness variations. During 1980–88, solar chromospheric variability was comparable to that observed in the stellar survey, but solar brightness variations were only one-quarter as large. This suggests that the Sun is in an unusually steady phase compared to similar stars, which means that reconstructing the past historical brightness record, for example from sunspot records, may be more risky than has been generally thought.