SYNCHROTRON EMISSION AS A TRACER OF THE OUTFLOW IN M82.

E.R. SEAQUIST
Department of Astronomy
University of Toronto
Toronto, Ontario M5S 1A1, Canada

NILS ODEGARD
General Sciences Corporation
Goddard Space Flight Center
Code 685.3, Greenbelt, MD 20771, U.S.A.

ABSTRACT. We report the discovery of radio synchrotron emission from the outflow in M82. The brightness morphology and radio spectral index distribution add new insights into the physical processes and origin of the wind, which are briefly discussed in this paper.

1. INTRODUCTION

It is now well established that M82 is undergoing mass outflow from its nuclear region, in accordance with evidence from optical spectroscopic data, molecular line data, and the morphology of its X-ray emission (eg. McCarthy, Heckman, and van Breugel 1987, Nakai et al. 1987, and Fabbiano 1988). The wind is possibly in the form of a bipolar outflow at an optically determined speed of 600 km s^{-1} (Bland and Tully 1988).

We report in this paper the discovery of radio synchrotron emission at several wavelengths associated with this outflow detected with the VLA and Westerbork radio telescopes*. The emission takes the form of a substantial nonthermal radio halo surrounding M82. The relativistic electrons which emit this radiation must necessarily be convected outward by the wind, and therefore must trace its morphology.

The synchrotron halo is extremely faint compared to the bright nuclear emission. The key factor in the success of our observation is the high dynamic range achieved, which exceeds 10,000 in all maps. In this paper we confine our attention primarily to the VLA 6 cm and 20 cm maps.

*The VLA is part of the National Radio Astronomy Observatory which is operated by Associated Universities Inc., under a cooperative agreement with the National Science Foundation. The WSRT is operated by the Foundation for Research in Astronomy which is financially supported by the Netherlands Organization for Scientific Research.

H. Bloemen (ed.), The Interstellar Disk-Halo Connection in Galaxies, 281–285.

2. RADIO MAPS AND THEIR INTERPRETATION

Figure 1 shows the radio data in various forms. The top panel shows the 20cm map made from data taken with the C and D configurations combined and superposed on a continuum photograph. The radio halo shown is about 8 kpc in diameter which is far larger than any radio emitting feature of M82 so far known. Of particular interest is the asymmetry with respect to the disk, which we return to at the end of the paper. The middle panel shows the same radio map (cropped) superposed on an H alpha photograph. The radio supernova remnants studied by Kronberg et al. (1985) are confined to a region roughly bounded by the inner contour of this map. The bottom panel shows a 6-20 cm spectral index map overlaid on the same photograph and scale as the middle panel. This map was made from 6 cm D-Array and 20 cm C-Array maps, comprising essentially identical uv plane coverage. Note that the spectral index distribution is plotted only on the inner region brightness distribution since the 6 cm emission becomes too weak in the outer region for a reliable measurement to be obtained.

The spectral index varies from about -0.5 in the nuclear region to about -1.0 in a plateau within a distance of 1 kpc from the nucleus. The steepest gradient is

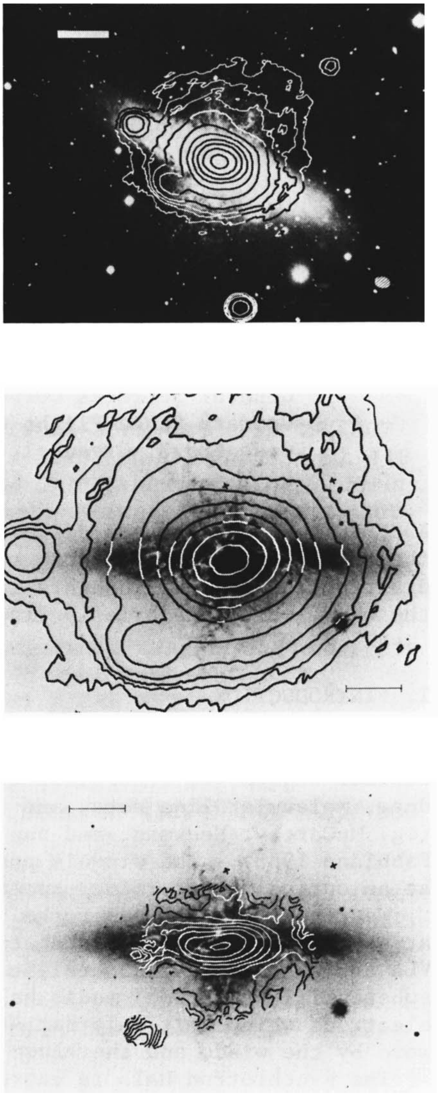

Figure 1. Top: 20 cm C+D configuration VLA map superposed on an optical continuum photograph of M82 from Sandage and Miller (1964). The bar at the upper left is 2 arcmin. Contours are: 1.0 mJy x (1.3,1.9,2.5,4,10, 30,100,300,1000,3000). Middle: The same map superposed on an H alpha photograph from Lynds and Sandage (1963). The bar at the lower right is 1 arcmin. Bottom: 6-20 cm spectral index map prepared from maps with identical uv plane coverage superposed on the Lynds and Sandage photograph with same scale as above (middle). Contours are: -1.3, -1.2, -1.1, -1.0, -0.9, -0.8, -0.7, -0.6, -0.5. The maximum contour at the nucleus is -0.5.

roughly parallel to the minor axis of M82. Similar variations in spectral index were found between 49 and 21 cm (Westerbork data) and 90 and 20 cm (VLA data). These maps are not shown. An important point here is that this spectral index gradient cannot be caused primarily by different admixtures of nonthermal and thermal emission. The amount of thermal emission in the disk is too small (cf Seaquist, Bell, and Bignell 1985; Ho, Beck, and Turner 1990). Therefore the variation must be predominantly caused by a spatial variation in the nonthermal spectral index, which in turn implies a variation in the energy spectral index of the relativistic electrons. Such a gradient would be anticipated in the presence of the M82 outflow because of Inverse Compton (IC) scattering by these electrons off the IR photons from the starburst region in the nucleus. In fact the losses by this mechanism would be expected to exceed those due to synchrotron losses which would produce a similar steepening (eg Rieke et al. 1980).

3. AN ILLUSTRATIVE MODEL FOR THE SPECTRAL INDEX VARIATION

We consider a simple model to account for the variation in spectral index with radius along the minor axis. The following assumptions are made:

(1) Relativistic electrons are transported by convection alone.
(2) The electrons lose energy by IC losses and adiabatic expansion.
(3) The radiation field and wind density follow an inverse square law. The IR luminosity is 1.82×10^{44} erg s^{-1}.
(4) The magnetic field follows an inverse linear law (similar to the behaviour of the equipartition field).
(5) No particle re-energization occurs in the wind.

Figures 2(a) and 2(b) show the results of the model calculations for two forms of the inverse square law. The form in Figure 2(b) is a softened version of the inverse square law (quantities $\propto (r+a)^{-2}$ with a = 200 pc. This form was used as a more realistic representation near the origin (the nucleus) where the sources are extended. Comparison with observation yields two noteworthy points.

The first is that the model does not predict the plateau in the spectral index at a value of -1.0. Possible implications of this are that either particle re-energization in the wind is occuring or that particle diffusion plays an important role in the transport mechanism. The spectral index behaviour is not unlike that expected for the 1-D models of Lerche and Schlickeiser (1980) incorporating both convection and diffusion. The second is that a comparison between the initial decline in spectral index with the model curves suggests outflow speeds in the range of 1000-3000 km s^{-1} are plausible. Note that such speeds are significantly higher than that inferred from optical data.

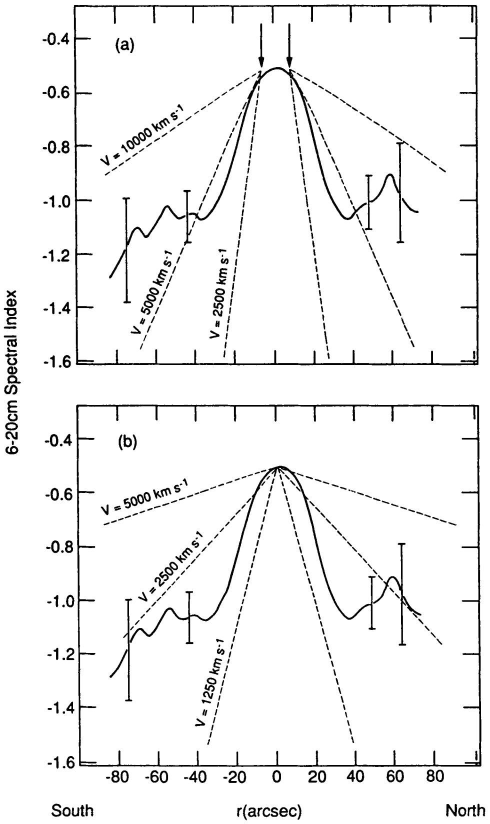

Figure 2. Profile of the 6-20 cm spectral index along the minor axis (solid curve) compared with that predicted for the emissivity from the simple outflow models described in the text (dashed curves). The error bars shown are +/- 0.1 and +/- 0.2 and are due to noise in the maps. Errors at lower radii are essentially negligible. The top panel (a) is for inverse square laws for the densities of the wind and radiation field energy, and an inverse linear law for the magnetic field. Arrows at r_0=100 pc mark the assumed particle injection site. The bottom panel (b) is identical except for the addition of a "softening parameter" a = 200 pc to the radius r in the above laws. This gives a more realistic representation of the dependences at small r, and the particle injection site is r = 0.

4. MODEL INDEPENDENT CONCLUSIONS

There are some conclusions that we have made that are not based on the above simple model. By assuming equipartition conditions in the wind, we can estimate the number of relativistic electrons available to produce IC scattering. We conclude that only a few percent of the X-ray emission in the halo of M82 could be produced by IC scattering. Therefore, most of the X-ray emission must be produced by hot gas. Secondly, the ratio of the energy in the form of relativistic particles to that in the form of thermal and kinetic energy in the wind is about 2 percent. This is consistent with the corresponding ratio in supernova remnants and is therefore consistent with a supernova origin for the wind and associated relativistic particles.

Finally, we return to the question of the asymmetry in the brightness distribution. Possible explanations include an asymmetry in the distribution of supernovae with respect to the disk of M82, or a termination shock in the outflow produced by a southward movement of the galaxy with respect to the intergalactic medium (IGM). The latter explanation is particularly appealing because of the sharp gradient in brightness at the southern edge. Gottesman and Weliachew (1977) mapped the region in HI and showed indeed that there is an HI envelope surrounding both M81 and M82. The ambient density in this region is plausibly 2×10^{-3} cm^{-3} obtained by inspecting their column density map. This density would be sufficient to produce a termination shock in the observed region if the IGM at this density were flowing northward relative to M82 by about 100 km s^{-1}.

5. CONCLUSION

Our conclusions may be summarized as follows:

(a) The outflow in M82 is visible in synchrotron radiation.
(b) IC losses are evident in the steepening of the radio spectrum, though this process is not a major contributor to the observed halo X-ray emission.
(c) Particle acceleration and/or diffusion in the wind may be important.
(d) Outflow speeds of 1000-3000 km s^{-1} are inferred from the spectral index profiles, which significantly exceeds the optically determined values.
(e) The fraction of the wind energy in the form of relativistic particles is consistent with a supernova origin.
(f) A termination shock produced by IGM may be shaping the observed halo of M82.

ACKNOWLEDGMENTS

This research was supported by an operating grant from the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

Bland, J. and Tully, R.B. (1988) Nature 334, 43
Fabbiano, G. (1988) Ap. J. 330, 672
Gottesman, S.T. and Weliachew, L. (1977) Ap. J. 211, 47
Ho, Paul T.P., Beck, Sara C., and Turner, Jean L. (1990) Ap. J. 349, 57
Kronberg, P.P., Biermann, P., and Schwab, F.R. (1985) Ap. J. 291, 693
Lerche, I. and Schlickeiser, R. (1980) Ap. J. 239, 1089
Lynds, C.R. and Sandage, A.R. (1963) Ap. J. 137, 1005
McCarthy, P.J., Heckman, T., and van Breugel, W. (1987) A.J. 93, 264
Nakai, N., Hayashi, M., Handa, T., Sofue, Y., Hasegawa, T., and Sasaki, M. (1987) Pub. Ast. Soc. Japan 39, 685
Rieke, G.H., Lebofsky, M.J., Thompson, R.I., Low, F.J., and Tokunaga, A.T. (1980) Ap. J. 238, 24
Sandage, A.R. and Miller, W.C. (1964) Science 144, 405
Seaquist, E.R., Bell, M.B., and Bignell, R.C. (1985) Ap. J. 294, 546