PARTICLE ACCELERATION IN THE DISK-HALO SYSTEM

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ABSTRACT. The recent observations of the nonthermal properties of the halo of our Galaxy at radio and γ-ray wavelengths are summarized. Radio and γ-ray data show a similar spectral flattening with Galactic height towards the anticenter direction, which is interpreted as a cosmic-ray effect. Several theoretical explanations for the flattening of the energy spectra of the radiating cosmic-ray electrons (in the radio) and nucleons (in γ-rays) are reviewed including propagation of cosmic rays in an accelerating Galactic wind and the presence of cosmic-ray sources with flat energy spectra in the halo.

1. INTRODUCTION

The formation of cosmic-ray halos in galaxies is a still unsolved problem of high-energy astrophysics: do the cosmic-ray particles diffuse or convect away from their sites of origin which for relativistic electrons definitely and for cosmic-ray nucleons probably are located inside galaxies? Some insight may be gained from the recent observations of significant cosmic-ray spectral differences in various regions of the disk-halo system reported both for cosmic-ray electrons from studies of the radio continuum background (Reich and Reich, 1988b) and for cosmic-ray nucleons from studies of the diffuse Galactic gamma-ray emission (Bloemen, 1987; Bloemen et al., 1988). Radio studies exist for the edge-on galaxies NGC 4631 (Hummel and Dettmar, 1990) and NGC 891 (Hummel, 1990). After summarizing the relevant Galactic observations I investigate several theoretical interpretations of these measurements.

2. SUMMARY OF RELEVANT OBSERVATIONS

2.1 Radio continuum background at 408 and 1420 MHz

Based on radio continuum surveys at 408 MHz (Haslam et al., 1982) and 1420 MHz (Reich, 1982; Reich and Reich, 1986) Reich and Reich (1988a) have presented a map of spectral indices of the northern sky with an

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angular resolution of 2° and an absolute spectral index error of ~0.1. At these frequencies the radio continuum is the sum of thermal free-free emission in the ionized interstellar medium (intensity spectrum $I \propto \nu^{-\alpha}$, $\alpha = 0.0-0.1$) and synchrotron emission of relativistic electrons of Lorentz factor $\gamma \simeq 1.5 \cdot 10^4\,[\nu(\mathrm{GHz})/B(\mu G)]^{1/2}$ in Galactic magnetic fields of strength B whose intensity spectrum is of power-law type $I \propto \nu^{-\alpha}$, $\alpha = (s-1)/2$, if the relativistic electron energy spectrum is of power-law type, $N(\gamma) \propto \gamma^{-s}$. The radio study shows significant variations of the spectral index of the brightness temperature $T_b \propto \nu^{-\beta}$, $\beta = 2+\alpha$, along the Galactic plane and from the plane toward higher Galactic latitudes. Most noteworthy is the reported *flattening* of spectral indices with increasing latitude both in the inner and outer Galaxy (see Figure 1). Towards the outer Galaxy $\beta(|b| = 0°) = 2.7-2.8$ near the plane and β reduces to 2.5–2.6 at $|b| \simeq 30°$. If correcting for the thermal emission in the plane Reich and Reich (1988) have found that the nonthermal spectral index β_{nth} flattens from a value 2.85 in the plane $|b| \simeq 0°$ by $\Delta\beta = 0.35 \pm 0.2$ with increasing latitude. Towards the inner Galaxy the nonthermal spectral index varies from $\beta_{nth} \simeq 3.1$ in the plane to values of $\beta_{nth} \simeq 2.7$ at high latitudes.

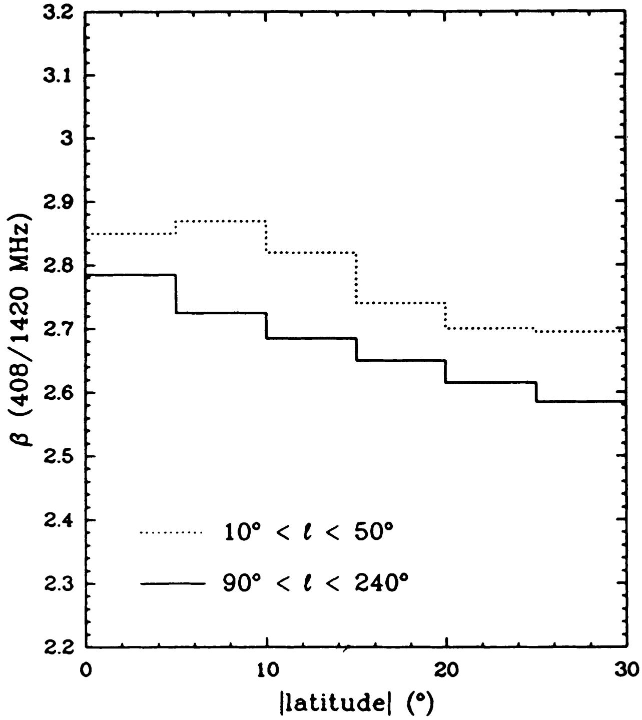

Figure 1. Latitude distributions of the spectral index β of the Galactic radio emission at 408 and 1420 MHz ($T_b \propto \nu^{-\beta}$) where regions above and below the Galactic plane are combined (from Bloemen et al., 1988).

2.2 Diffuse galactic gamma-ray emission above 300 MeV

Cosmic gamma rays with energies above 300 MeV originate predominantly ($\gtrsim$ 80 percent) from the decay of neutral pions produced in inelastic p-p, p-He, α-p collisions of cosmic-ray nucleons of energy greater than 3 GeV (Stecker, 1973; Dermer, 1986) with atoms and molecules of the interstellar gas, with a minor ($\lesssim$ 20 percent) contribution from nonthermal bremsstrahlung of relativistic electrons (0.6-10 GeV) where most of these electrons may be of secondary origin from the decay of charged pions $\pi^\pm \to \mu^\pm \to e^\pm$ produced in the same inelastic collisions as the neutral pions (Schlickeiser, 1981, 1982). Inverse Compton scattering of low-frequency microwave, infrared and starlight photons by cosmic-ray electrons plays a negligible role (contribution less than a few percent). The energy spectrum of the generated γ-rays at high photon energies (> 0.5 GeV) reflect the energy spectrum of the cosmic-ray nucleons: if the latter is of power-law type $\propto E_{CR}^{-s}$ the γ-ray number spectrum is also of power-law type $\propto E_\gamma^{-\Gamma}$ with $\Gamma = (s-2b)/(1-b)$ where b denotes the energy dependence of the pion multiplicity $\xi \propto E_{CR}^{b}$ (Stecker, 1971). Measured variations in Γ directly indicate variations in the nucleon spectral index s.

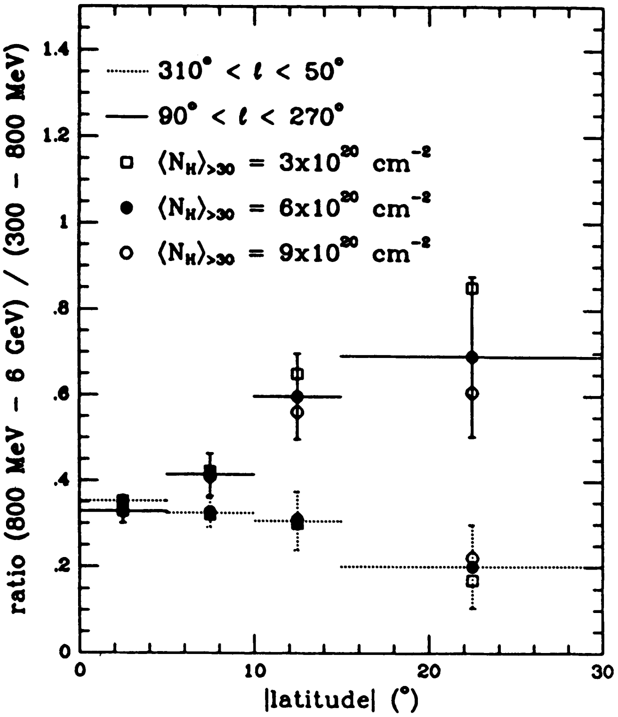

Figure 2. Latitude distribution of the γ-ray colour towards the inner and outer Galaxy after subtraction of the background levels (from Bloemen et al., 1988)

Using the COS-B data above 300 MeV, excluding regions with radius 8° around the well-known γ-ray point sources Crab pulsar, Vela pulsar and CG195+4 and subtracting the isotropic (extragalactic and instrumental) background, Bloemen et al. (1988) determined spectral variations in Γ from the γ-ray colour C = I(0.8−6 GeV)/I(0.3−0.8 GeV) calculated from the γ-ray intensity in two energy intervals. The variation of the γ-ray colour with Galactic latitude in the inner and outer Galaxy is shown in Figure 2. The rising values of C in the outer Galaxy from 0.33±0.03 at $|b| \simeq 0°$ to 0.68±0.18 at $|b| \simeq 15°-30°$ suggest a strong flattening of the nucleon spectrum with latitude. Towards the inner Galaxy the data are consistent with a constant value of $C \simeq 0.30$.

2.3 Conclusions from observations

Since radio and γ-ray data show a similar gradual flattening in their spectral behaviour we interpret this as a cosmic-ray effect that the energy spectra of the radiating cosmic-ray electrons and nucleons flatten with increasing latitude. Figure 3 shows the derived spectral flattening in the respective energy distributions $n(E) \propto E^{-\Gamma}$, indicating in both cases a flattening by $\Delta\Gamma \simeq 0.4-0.6$ from $|b| \simeq 0°$ and 30° in the outer

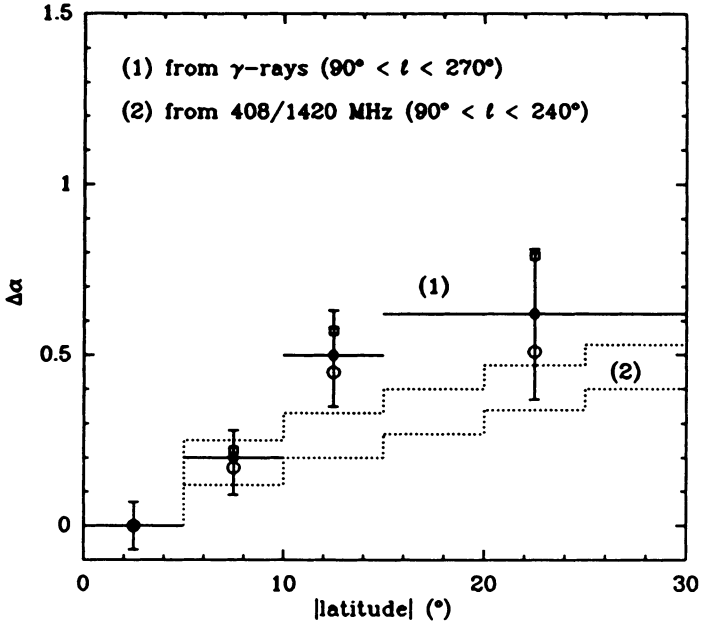

Figure 3. Variation of the cosmic-ray spectral index α ($n(E) \propto E^{-\alpha}$) as a function of Galactic latitude. $\Delta\alpha(b) \equiv \alpha(0)-\alpha(b)$ is estimated from the γ-ray colour for cosmic-ray nucleons and from the radio continuum emission at 408 and 1420 MHz for cosmic-ray electrons (from Bloemen et al., 1988)

Galaxy. First, this result implies that the measured cosmic ray spectra at the position of the solar system are *not* representative for the whole Galaxy which affects total cosmic-ray power estimates of our Galaxy. Secondly, this finding is an important constraint on cosmic-ray acceleration and transport models, which needs to be explained by any viable model of cosmic-ray origin. Bloemen et al. (1988) have pointed out that their results can be accounted for in remarkable detail by the Galactic wind model for cosmic-ray propagation where spectral flattenings have been predicted (Lerche and Schlickeiser, 1981, 1982a,b) due to the combined action of adiabatic deceleration in the accelerating Galactic wind and energy-dependent spatial diffusion. It is the purpose of the remainder of this paper to investigate additional interpretations of these observations.

3. PARTICLE ACCELERATION IN THE DISK-HALO SYSTEM

The radio and γ-ray observations summarized above refer to the steady-state equilibrium spectrum of cosmic rays $N(\gamma,\vec{r})$ that results from the balance of sources (injection by point sources as supernova remnants, pulsars), sinks (leakage from the Galaxy, catastrophic losses as fragmentation and spallation) and interaction processes of cosmic rays with cosmic matter, radiation and electromagnetic fields on their way from their sites of origin to us. This balance is described by the convection-diffusion cosmic-ray transport equation

$$-\frac{dN}{dt} = \mathrm{div}\ (\kappa(\gamma,\vec{r})\ \mathrm{grad}\ N - \vec{V}(\vec{r})N) + \frac{\partial}{\partial\gamma}\left[\left\{\frac{1}{3}\ \mathrm{div}\ \vec{V}(\vec{r})\gamma - \gamma(\gamma,r)\right\}N\right]$$

$$+ \frac{\partial}{\partial\gamma}\left[\gamma^2\ a_2(\gamma,\vec{r})\ \frac{\partial}{\partial\gamma}\left\{N\gamma^{-2}\right\}\right] - \frac{N}{T_F(\gamma,\vec{r})} = -Q(\gamma,\vec{r}) \qquad (1),$$

that contains terms representing spatial diffusion with diffusion coefficient $\kappa(\gamma,\vec{r})$, convection and adiabatic deceleration determined by the cosmic-ray bulk speed $\vec{V}(\vec{r})$, energy diffusion with diffusion coefficient $a_2(\gamma,\vec{r})$, spontaneous energy loss processes $\gamma(\gamma,\vec{r})$ and catastrophic losses with loss time $T_F(\gamma,\vec{r})$. The source term $Q(\gamma,\vec{r})$ represents injection from point sources. A recent derivation of equation (1) can be found in Kirk et al. (1988) and Schlickeiser (1989). Spatial and energy diffusion result from the interaction of cosmic rays with interstellar magnetohydrodynamic turbulence. For Alfvén waves propagating parallel and antiparallel to the ordered magnetic field the two diffusion coefficients are related as (Dung and Schlickeiser, 1990a,b)

$$\kappa(\gamma,\vec{r})\ a_2(\gamma,\vec{r}) = V_A^2\ \gamma^2\ G(h_c,\sigma^\pm)\ F(h_c,\sigma^\pm) \qquad (2),$$

where the two dimensionless functions G and F depend on the magnetic helicity of the parallel (σ^+) and antiparallel (σ^-) waves and the cross helicity (h_c) of the Alfvénic turbulence, that is related to the fractional abundance of the parallel to total waves r as $h_c = 2r+1$. $V_A = 2.18.10^{11}$ B(G) $n_e^{-1/2}(\mathrm{cm}^{-3})$ is the Alfvén speed.

The cosmic-ray bulk velocity is the sum of the interstellar gas velocity $\vec{U}(\vec{r})$ and some fraction of the Alfvén velocity $\vec{V}_A(\vec{r})$,

$$\vec{V}(\vec{r}) = \vec{U}(\vec{r}) + V_A(\vec{r})\ H(h_c, \sigma^{\pm}) \qquad (3),$$

where the dimensionless function $H(h_c, \sigma^{\pm})$ depends again on the helicities of the interstellar turbulence, and is restricted to values between −1 and +1 (Dung and Schlickeiser, 1990b). For vanishing interstellar gas velocity, $\vec{U} = \vec{0}$, there still are convective terms in equation (1) if $H \neq 0$.

The functions $\dot{\gamma}(\gamma, \vec{r})$ and $T_F(\gamma, \vec{r})$ describe continuous and catastrophic energy loss processes and differ for cosmic-ray electrons and nucleons (see the discussion in Schlickeiser, 1986). For relativistic electrons $T_F{}^e = 0$ and

$$-\dot{\gamma}_e = 6.10^{-14}\, n_e \left\{ 18.56 \left[1 + 1.35.10^{-2} \ln \frac{\gamma}{n_e}\right] + 2.32.10^{-3}\, \gamma (\ln \gamma + 0.36) + \frac{4}{9}\, \gamma^2\, \frac{W_{ph} + \frac{B^2}{8\pi}}{m_e c^2\, n_e} \right] \qquad (4)$$

in a fully ionized interstellar medium of density n_e in cm^{-3}, target photon energy density W_{ph} and magnetic field strength B.

An additional constraint for any model of cosmic-ray origin is the requirement to reproduce the measured cosmic-ray nucleon and electron energy spectra at the position of the solar system, which at energies above 1 GeV are straight power laws over more than 4 decades in energy for nucleons (Burnett et al., 1983; Grunsfeld et al., 1988) and over more than 2 decades in energy for electrons (Nishimura et al., 1990).

There are several theoretical alternatives on the basis of equation (1) to explain the given set of observations but only few of them have been worked out thoroughly. They can be divided into two classes (a) propagation effect, (b) source effect. Let us consider each in turn.

3.1 Propagation effect

Lerche and Schlickeiser (1981, 1982a,b) have pointed out that spectral flattenings are signatures of the presence of convective terms in the cosmic-ray transport equation coupled with energy-dependent spatial diffusion. And it is indeed remarkable how well their original theoretical predictions match the now available observations (see the discussion in Bloemen et al., 1988). Recently their calculations have been extended analytically to thick disk source distributions by Pohl and Schlickeiser (1990), see also Pohl (1990), and numerically by Van der Walt (1990).

3.2 Source effect

3.2.1 Anomalous Halo Cosmic-Ray Component. Another interpretation of the spectral flattenings is the existence of a new component of cosmic rays in the halo which has a flatter energy spectrum than cosmic rays at the solar system. This Anomalous Halo Cosmic Ray Component (AHCRC) may well be associated with particle acceleration at the Galactic wind termination shock (Jokipii and Morfill, 1985, 1987). As an aside note that in the interplanetary medium there exists an anomalous cosmic-ray component associated with the solar wind termination shock (for review see Webber, 1989) and it is fair to speculate that a similar phenomenon occurs on Galactic scales. The AHCRC cannot make a strong contribution to the locally measured cosmic-ray flux, which can be accounted for by the Galactic modulation of the AHCRC in the outwardly accelerating Galactic wind (Ahlen et al., 1982), if the location of the Galactic wind termination shock is far enough away from the Galactic plane.

I want to make two critical remarks to this model:

(1) the explanation by particle acceleration at the termination shock relies on the existence of a Galactic wind and a dense enough intergalactic medium to generate a termination shock. At the moment it is not clear that these conditions indeed exist in the interstellar and intergalactic medium. Moreover, the concept of a Galactic wind already offers an explanation of spectral flattenings as a propagation effect, as noted in Section 3.1, so there is no necessity to postulate this new cosmic-ray component;

(2) in the halo region radiation losses dominate ionization, Coulomb and bremsstrahlung losses for Lorentz factors larger than

$$\gamma > 290\ (n_e/10^{-3}\ \mathrm{cm}^{-3})^{1/2} \qquad (5),$$

since the halo gas densities are small ($n_e \simeq 10^{-3}$ cm^{-3}) and $[W_{ph}+(B^2/8\pi)] \gg W(2.7\mathrm{K}) = 0.25$ eV cm^{-3}. In order to obtain a flat steady-state equilibrium electron spectrum $N(\gamma) \propto \gamma^{-2.3}$, the electron source spectrum has to be even flatter as $Q(\gamma) \propto \gamma^{-1.3}$ to account for the spectral index steepening by $\Delta\alpha = 1.0$ by the radiation losses. Such flat power-law spectra for the electrons of the AHCRC are difficult to reconcile with the standard theory of diffusive shock-wave acceleration (for review see Drury, 1983; Blandford and Eichler, 1987), which yields $Q(\gamma) \propto \gamma^{-s}$ and $s = (r+2)/(r-1)$ being determined by the shock's compression ratio $r \leq 4$. The smallest s can get is $s = 2$ for $r = 4$. Either this explanation does not work or the standard theory of shock-wave acceleration has to be modified. An important modification has been proposed by Dröge et al. (1987) and Schlickeiser and Fürst (1989), which is based on the inclusion of energy diffusion of particles in the Alfvénic turbulence near the shock wave. They have shown that in the case of low values of the upstream plasma beta $\beta_p = c_{s1}{}^2/V_{A1}{}^2 = 8\pi nkT/B_0{}^2$ this modification is important and produces very flat power-law spectra ($s \to 1$ for $\beta_p \to 0$) for the accelerated particles. This brings us to a second explanation of spectral flattenings which relies on flat-spectrum sources in the halo.

3.2.2 Flat-Spectrum Sources in the Halo. Observations of the radio spectral indices of shell-type supernova remnants in the Galaxy and the Magellanic Clouds show dispersion around $\langle\alpha\rangle = 0.5$ with a width $\sigma_\alpha \simeq 0.3$, which points to a dispersion in the energy spectra of the radiating electrons around $\langle s\rangle = 2.0$ with a width $\sigma_s = 0.6$. While this dispersion is difficult to understand by the standard model of shock-wave acceleration the inclusion of energy diffusion in the turbulence near the shock provides a straightforward explanation (see discussion in Dröge et al. (1987) and Schlickeiser and Fürst (1989)).

Brecher and Burbidge (1972) have emphasized an important consequence of dispersion in the spectral indices of the source spectra $Q(\gamma) \propto \gamma^{-p}$. If the probability of a certain value of p is determined by a Gaussian distribution

$$n(p) = \frac{n_0}{\sqrt{2\pi\mu}} \exp\left[-\frac{(p - \langle p\rangle)^2}{2\mu}\right] \qquad (6),$$

the equilibrium spectrum $N(\gamma)$ for the very simple version $N(\gamma)/T(\gamma) = Q(\gamma)$ of equation (1) is

$$N(\gamma) = T(\gamma) \int_0^\infty dp \; (\gamma/\gamma_1)^{-p} \, n(p) \propto T(\gamma) \; \gamma^{-\Gamma(\gamma)} \qquad (7)$$

with $\Gamma(\gamma) = \langle p\rangle - (\mu/2) \ln (\gamma/\gamma_1)$. With increasing energy the effective spectral index $\Gamma(\gamma)$ becomes flatter. This is a consequence of the fact that sources with the flattest spectra dominate in the superposition at large energies. So this simple argument can explain the spectral flattenings in the halo.

However, there is a contradiction with the measured energy spectra at the solar system, which apparently do not show this effect. And in fact Brecher and Burbidge (1972) have used this contradiction to argue against a Galactic origin of cosmic rays. But I think we can still use this effect of flattening if we can argue that sources with flat spectra occur only in the halo region, i.e. that low values of the plasma beta of the interstellar medium preferentially occur in the halo region than in the disk region. It would be also interesting to investigate whether flat-spectrum shell-type supernova remnants are preferentially located at large Galactic heights. This theoretical alternative can turn out to be very useful but more detailed theoretical and observational work is needed to assess its importance.

4. CONCLUSIONS

We have summarized the recent observations of the nonthermal properties of the halo in our Galaxy. Most noteworthy are the spectral flattenings of both the radio continuum and diffuse γ-ray background emission with Galactic height towards the anticenter direction. Since the radio and γ-ray data simultaneously show this flattening this is certainly a cosmic-ray effect that the energy spectra of the radiating cosmic-ray electrons (in the radio) and nucleons (in γ-rays) flatten with increasing latitude. We investigate several theoretical interpretations of these measurements including the well-known spectral flattening resulting from the presence of convective terms (convection and adiabatic deceleration in an accelerating Galactic outflow) in the cosmic-ray transport equation coupled with energy-dependent spatial diffusion, the possible existence of a new anomalous halo cosmic-ray component with a flat energy spectrum, and the flattening resulting from the dispersion in the power-law spectral indices of the cosmic-ray sources. While some interpretations still have to be worked out more thoroughly before a final assessment, we think that the interpretation as a propagation effect in an accelerating Galactic outflow is at present the best approach, since this model can remarkably well account in a quantitative fashion for the observed properties of the nonthermal halo.

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5. REFERENCES

Ahlen, S.P., Price, P.B., Salamon, M.H., Tarle, G. (1982) *Ap. J.* **260**, 20
Blandford, R.D., Eichler, D. (1987) *Phys. Rep.* **154**, 1
Bloemen, J.B.G.M. (1987) *Ap. J.* **317**, L15
Bloemen, J.B.G.M., Reich, P., Reich, W., Schlickeiser, R. (1988) *Astr. Ap.* **204**, 88
Brecher, K., Burbidge, G.R. (1972) *Ap. J.* **174**, 253
Burnett, T.M. et al. (1983) *Phys. Rev. Lett.* **51**, 1010
Dermer, C.D. (1986) *Astr. Ap.* **157**, 223
Dröge, W., Lerche, I., Schlickeiser, R. (1987) *Astr. Ap.* **178**, 252
Drury, L.O.C. (1983) *Rept. Progr. Phys.* **46**, 973
Dung, R., Schlickeiser, R. (1990a) *Astr. Ap.* (in press)
Dung, R., Schlickeiser, R. (1990b) *Astr. Ap.* (in press)
Grunsfeld, J.M., L'Heureux, J., Meyer, P., Müller, D., Swordy, S.P. (1988) *Ap. J.* **327**, L31
Haslam, C.G.T., Salter, C.J., Stoffel, H., Wilson, W.E. (1982) *Astr. Ap. Suppl.* **47**, 1
Hummel, E. (1990) these proceedings
Hummel, E., Dettmar, R.-J. (1990) *Astr. Ap.* (in press)
Jokipii, J.R., Morfill, G.E. (1985) *Ap. J.* **290**, L1
Jokipii, J.R., Morfill, G.E. (1987) *Ap. J.* **312**, 170
Kirk, J.G., Schneider, P., Schlickeiser, R. (1988) *Ap. J.* **328**, 269
Lerche, I., Schlickeiser, R. (1981) *Ap. Lett.* **22**, 161
Lerche, I., Schlickeiser, R. (1982a) *Astr. Ap.* **107**, 148
Lerche, I., Schlickeiser, R. (1982b) *M.N.R.A.S.* **201**, 1041
Nishimura, J. et al. (1990) *Proc. 21st Intern. Cosmic Ray Conf. (Adelaide),* Vol. **3**, p. 213
Pohl, M. (1990) these proceedings

Pohl, M., Schlickeiser, R. (1990) *Astr. Ap.* (in press)
Reich, W. (1982) *Astr. Ap. Suppl.* **48**, 219
Reich, P., Reich, W. (1986) *Astr. Ap. Suppl.* **63**, 205
Reich, P., Reich, W. (1988a) *Astr. Ap. Suppl.* **74**, 7
Reich, P., Reich, W. (1988b) *Astr. Ap.* **196**, 211
Schlickeiser, R. (1981) *Fortschr. d. Phys.* **29**, 95
Schlickeiser, R. (1982) *Astr. Ap.* **106**, L5
Schlickeiser, R. (1986) in *Cosmic Radiation in Contemporary Astrophysics*, ed. M.M. Shapiro, Reidel, Dordrecht, p. 27
Schlickeiser, R. (1989) *Ap. J.* **336**, 243
Schlickeiser, R., Fürst, E. (1989) *Astr. Ap.* **219**, 192
Stecker, F.W. (1971) *Cosmic Gamma Rays*, Mono Book Corp., Baltimore
Stecker, F.W. (1973) *Ap. J.* **185**, 499
Van der Walt, D.J. (1990) *Ap. Space Sci.* **168**, 23
Webber, W.R. (1989) in *Cosmic Abundances of Matter*, ed. C.J. Waddington, AIP Conf. 183, p. 100