A and A Manuskript-Nr.
(will be inserted by hand later)

Your thesaurus codes are:
02.01.1, 02.01.2, 02.05.1, 08.02.1, 09.03.2, 13.18.5

ASTRONOMY
AND
ASTROPHYSICS
29.6.1995

Cosmic rays

V. The nonthermal radio emission of the old nova GK Per - a signature of hadronic interactions?

Peter L. Biermann[1], **Richard G. Strom**[2], **Heino Falcke**[1]

[1] Max Planck Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
[2] Netherlands Foundation for Research in Astronomy, Radiosterrenwacht, P.O.Box 2, NL-7990 AA Dwingeloo, The Netherlands

Received; accepted

Summary. Using the model of particle acceleration in shocks in stellar winds developed by Biermann (1993) and Biermann and Cassinelli (1993) we demonstrate that the nonthermal radio emission spectrum from the cataclysmic variable binary star GK Per can be interpreted consistently. We propose that the radio spectrum results from hadronic secondary electrons/positrons, which, in the optically thin case, give a characteristic radio spectrum with a spectral index of $+1/3$ below a maximum and, for a strong shock in a wind slow compared to the shock speed, of -0.7 above the maximum. We test the proposed concept for consistency with the radio data for OB and Wolf Rayet stars as well as radiosupernovae. There is some evidence that this process is important for the radio emission from active galactic nuclei, both in compact and extended emission. We argue that such a radio spectrum is a unique characteristic for hadronic interactions.

Key words: Acceleration of particles, Accretion disks, Elementary particles, Close binary stars, Cosmic Rays, Radio continuum: stars

1. Introduction

1.1. The origin of cosmic rays

The origin of cosmic rays as observed near earth is still not fully settled. Recent work proposes that this origin can be attributed to three major sites, a) stellar explosions into the interstellar medium (ISM-supernovae), b) stellar explosions into a former stellar wind (wind-supernovae) , and c) powerful radio galaxy hot spots. The predictions were made in Biermann (1993, paper CR I), and in Rachen and Biermann (1993, paper UHE CR I). Tests on a) stellar winds were made in Biermann and Cassinelli (1993, paper CR II), on b) explosions into a homogeneous interstellar medium in Biermann and Strom (1993, paper CR III), on c) the chemical abundance and spectrum against air shower data in Stanev et al. (1993, paper CR IV), and on d) the ratio of wind-supernovae to ISM-supernovae and the implications for the chemical abundances of Helium and hydrogen in cosmic rays in Biermann et al. (1995). The chemical abundances and the predicted spectrum for the extragalactic component (paper UHE CR I) were checked against air shower data in Rachen et al. (1993, paper UHE CR II). This latter check provided an independent control on the spectrum and chemical composition of the galactic component beyond the knee, near $5\,10^6$ GeV. A definitive check on the chemical composition across the knee will probably be possible with the MACRO-EASTOP experiment (Battistoni and Navarra, priv. comm.), combining muon data with air shower data. Clearly, any concept of how particles, nuclei and electrons get injected and accelerated has to account for the nonthermal radio emission in other sites which are believed to be basically similar.

1.2. The nova GK Per

The nova GK Per, which exploded in 1901 and has been observed ever since with great care, is such a case. The radio spectrum of its shell has been observed (Reynolds and Chevalier 1984) to be a power law of spectral index $\approx -2/3$, which is close to the limiting spectrum of synchrotron emission from a shocked region in a stellar wind in the case that the shock is much faster than the wind speed (exactly $-2/3$). We note that this radio spectrum is quite unusual for novae (see, e.g., Hjellming 1990), since in other cases where radio emission has been detected, it can readily be understood as free-free emission. This is similar to the case of OB and WR stars (CR II), where free-free radio emission is also very common, and non-thermal radio emission is clearly less frequent (Abbott et al. 1986, Bieging et al. 1989). For OB and WR stars we have suggested that shocks in winds accelerate particles to sufficient energies to give the observed non-thermal radio emission. In Nath & Biermann (1994) we have been able to check the concept of shocks running through the winds of OB stars and then hitting a surrounding shell with the observed γ-ray line and continuum data.

In this paper we try to understand the radio emission from the shell of the nova GK Per in order to check the concepts described in the series of papers on the origin of cosmic rays, and develop them further.

Send offprint requests to: P.L. Biermann

The model which we have developed for strong shocks in stellar winds (see, MacFarlane & Cassinelli 1989, CR I and CR II) has been described in some detail in Biermann (1995). The model concentrates on spherical shockwaves, with a magnetic field orientation mostly parallel to the shock front, as is the case for a spherical shock advancing into an asymptotic Parker type wind. We note that in this case a north-south asymmetry can develop due to the possibility that the sign of the particle drifts differs in the two hemispheres (towards the pole in one hemisphere and towards the equator in the other, for instance). We propose this effect to explain the asymmetry in the radio emission in the radio shell of GK Per.

Therefore we explore in this paper the idea that the non-thermal radio emission from the shell produced by the nova GK Per is also due to a strong shock initiated in a wind by the outburst of 1901. For the wind we assume a Parker-type spiral magnetic field (see, e.g., Jokipii et al. 1977).

2. The low frequency turnover in the radio spectrum

2.1. The data for GK Per

The spectrum of GK Per has been published by Seaquist et al. (1989). We have reanalyzed the WSRT data at 49 and 92 cm, making full use of the redundancy technique to achieve high dynamic range and thereby reduce the interfering effects of background sources. This results in an upward revision of the flux densities S_ν at both wavelengths, and smaller errors. The flux density scale is based upon that of Baars et al. (1977), using 3C48 as a primary, and 3C295 as a secondary calibrator. The flux densities are 8.7 ± 0.5, 20.6 ± 1.6, 29 ± 3, 33 ± 10, 38 ± 6, and < 40 mJy at the frequencies 4.86, 1.49, 0.608, 0.408, 0.327, and 0.151 GHz, respectively. The improvement over previous data is the Westerbork points at 0.608 and 0.327 GHz. Our spectrum is shown in Fig. 1. It is clear that the high frequency spectrum turns over, gradually, somewhere below 1 GHz, suggesting either absorption or a low energy cutoff in the electron spectrum.

Fig. 1. The newly derived radio spectrum of GK Per using WSRT data in the redundancy mode. These newly derived data points are emphasized in this figure which is otherwise analoguous to the spectrum shown in Seaquist et al. (1989)

When we fit a powerlaw through the three high frequency data points, we obtain

$$S_\nu \;=\; (13.4 \pm 1.3\,\mathrm{mJy})\,(\frac{\nu}{2.69\,\mathrm{GHz}})^{-0.73\pm0.08}, \qquad (1)$$

where we have used the geometric mean between the high frequencies as reference. The deviation of the observed flux densities from this fitted powerlaw is 2 to 3 σ for each individual frequency only, but at all four lower frequencies this deviation is in the same direction, making it of interest to pursue; to have such a deviation occurring systematically is significant. Since systematic errors enter the individual errors, it is difficult to measure the significance of this systematic difference, but assuming the systematic errors to be fully accounted for in each individual error determination, then the combined significance is high, much higher than 3 σ. In the following this observation is the key to the arguments we will be presenting.

2.2. Interpretation

What is the physical origin for this downturn at low frequency? It is very difficult and quite unconvincing to attribute the cutoff to free-free absorption, or synchrotron self-absorption (Seaquist et al. 1989). We note that Seaquist et al. (1989) already mentioned the possibility of a low energy cutoff in the energetic electron distribution. A low energy cutoff in the electron distribution is a natural consequence of nucleus-nucleus interaction between cosmic ray particles and interstellar matter, primarily proton-proton (pp) interaction; this is due to the large rest mass of charged pions which are created in such collisons (neutral pions decay into photons, of course), and which then decay further, ultimately leaving neutrinos of various flavors and electrons and positrons. This topic of the injection of secondaries from energetic particle interaction with matter has been of classical interest (Hayakawa & Okuda 1962; Ginzburg & Syrovatskii 1964; Ekspong et al. 1966; Stecker 1971; and many others; recent references are Klemens 1987, Biermann & Strittmatter 1987, Sikora et al. 1987 and Mannheim 1993a, b).

The kinematics of the creation of a new particle like one or several charged pions in the center of mass frame of the encounter of the two protons reduce the energy available for the pion when the excess energy comes down to the scale of the proton rest mass, and so we expect the electron/positron distribution to deviate slightly from the ultimate power law below energies of a few GeV. Such a change is indeed observed in proper Monte-Carlo calculations (Daum & Biermann, in prep.). The peak of the production spectrum, when multiplied by energy to find the relevant maximum for synchrotron emission, is near 100 MeV: $\gamma_{e,min} \approx 200$. Thus the final electron/positron spectrum is the well known power law above a particle energy of order 5 GeV, but shows a low energy turnover and cutoff at about 100 MeV. Between 100 MeV and about 5 GeV the spectrum is somewhat flatter than the ultimate high energy spectrum.

Hence, the expected radio spectrum is a power law $S_\nu \sim \nu^{+1/3}$ in frequency ν below

$$\nu_{max} \;=\; 7.2\,10^8\;\mathrm{Hz}\,(\frac{\gamma_{e,min}}{200})^2\,\sin\theta_{cone}\,B_{0.5}, \qquad (2)$$

where we have referred the magnetic field at the actual location of the shock to the magnetic field at the equator at the reference radius by $B(shock) = 1.1\,10^{-3}\,\sin\theta_{cone}\,B_{0.5}$ from the assumption of a Parker wind topology; $B_{0.5}$ is the strength of the magnetic field at the equator at the reference radius of 10^{14} cm in units of 3 Gauss. θ_{cone} is the cone opening angle of the emission region.

The low frequency turnover is in the range $0.3 - 1.4$ GHz, and so this suggests a magnetic field strength of about 1.3 to 5.8 Gauss at the reference radius, and more if the cone angle of the observed emission is small. Here the latitude dependence of the magnetic field strength enters only linearly, and so the magnetic field implied here is the lower limit for the equatorial magnetic field strength. We thus estimate from the upper as well as lower limit the magnetic field to be of order 1 Gauss at the reference radius.

Above the frequency for the maximum in emission (corresponding to $\gamma_{e,min}$) the radio spectrum has the approximate form $S_\nu \sim \nu^{-0.7}$, for $U_1/V_W \gg 1$, but somewhat steeper than this for smaller shock velocities, with some steepening for the frequency range a factor of order 3000 above the frequency of maximum emission. Here U_1 is the shock velocity in the wind frame, and W is the wind velocity. We emphasize that a) this spectrum is optically thin, and b) the spectrum is very broad at the maximum of the flux.

We have used here the Fermi model for the multiplicity of the secondary pions; there is a weak modification for the spectrum of the secondaries when one considers the full kinematics of the encounter of the pp-collison, measured multiplicities and the thresholds (Daum & Biermann, in prep.).

This spectrum is valid for primary proton spectra of $E^{-7/3}$ which have been derived for strong shocks which are much faster than the wind; for steeper proton spectra such as expected for shocks which are slow compared to the wind the resulting secondary spectrum is also steeper, and so we can reconcile the observed radio spectrum and its error range with this suggestion.

This spectral behaviour of two well-specified power laws around a peak is thus *a characteristic signature of hadronic interactions*, and provides a clear statement: *Acceleration of nuclei, including protons, is clearly indicated by such a spectrum.* Then there ought to be corresponding γ-ray emission, as well as neutrino emission, which, however, usually is too weak to be detected. We note that the threshold for new particle production is a common signature for hadronic interactions, see, e.g., also Mannheim (1993a) leading quite generally to breaks between two different power laws. Whether such processes also help understand γ-ray bursts (e.g., Band et al. (1993)), which also seem to show such *nonthermal* spectra, is open at present.

3. Injection of secondary particles

3.1. Basic balance of injection and loss

In this main section of the paper we will derive the equivalent injection efficiency of secondary particles from p-p interactions in order to see whether we can explain the radio data and their implications for i) OB and WR stars, ii) radio supernovae, and most importantly, iii) GK Per. The basic question is to ask is whether we can explain the rather different injection efficiencies as due to primary injection from the thermal pool in some cases, and as secondary injection in all other cases; the test is the quantitative estimate of the efficiency derived and, also, obviously the spectrum of the particles.

We use the results and notation from CR II and define

$$\eta_p\,\rho\,U_1^2 \;=\; \int_{t_a}^{t_b} C_p\,t^{-7/3}\,E_{kin}\,dt. \tag{3}$$

with $t := p_p/(m_p c)$; here p_p is the momentum of a proton, E_{kin} its kinetic energy, U_1 the shock speed, and η_p an efficiency of converting shock kinetic energy to an energetic particle population. The integration limits t_a and t_b are from the beginning of the energetic particle population close to the thermal Maxwellian tail, to the maximum achievable; as long as $t_a \ll 1$ and $t_b \gg 1$ the integral is independent of their exact values. Below we will refer to the equivalent efficiency for electrons η_e directly obtained from observations, and our model for the emission region (see paper CR II). The density ρ above is the density in the wind of speed V_W and so we have

$$C_p \;=\; 26.9\,\eta_{p,-1}\,(\frac{\dot{M}_{-5}}{V_{W,-2}})\,U_{1,-2}^2\,\frac{1}{r_{14}^2}. \tag{4}$$

The units for C_p are cm^{-3}, $10^{-5}\,M_\odot$/yr for the mass loss, 10^{14} cm for the radius, 0.1 for η_p, and $10^{-2}\,c$ for the velocities. Then interactions between energetic protons and thermal protons in the wind produce secondary electrons and positrons as a rate per unit volume

$$C_p\,\int \gamma_p^{-7/3}\,\langle\sigma_p\,f(\gamma_p)\rangle\,c\,n\,d\gamma_p, \tag{5}$$

where $f(\gamma_p)$ is the multiplicity. The combination of cross section and multiplicity $\langle\sigma_p\,f(\gamma_p)\rangle$ we approximate as a constant of value $40\,10^{-27}\,f_\Delta$ cm^2; there are various calculations of this in the classical literature, e.g. Gould & Burbidge (1968), Stecker (1971), Stephens & Badhwar (1981); we take the particular value from a calculation by Niemeyer (1995), which improves upon Gould & Burbidge (1968) and agrees with Stecker (1971), and obtain an estimate for f_Δ of 1.4. As a lower threshold we use the approximation $\gamma_p = 1.4$ from the threshold condition for the Delta-resonance (derived from the energy where the cross section falls to half its peak value).

The rate of generation of secondary electrons/positrons is then

$$1.53\,10^{-7}\,\eta_{p,-1}\,f_\Delta\,(\frac{\dot{M}_{-5}}{V_{W,-2}})^2\,U_{1,-2}^2\,\frac{1}{r_{14}^4}. \tag{6}$$

Here we have made no distinction between hydrogen and other nuclei in the gas of the stellar wind, but have just counted all nucleons.

We consider the shock frame as it advances. Then we also have losses, first of all dilution losses - from the continuity equation in spherical coordinates - with the rate

$$2\,\frac{V_W + U_1}{r}, \tag{7}$$

and the losses downstream from the diffusive Fermi process (see Drury 1983) of

$$(1-\zeta)\,\frac{U_1}{r}, \tag{8}$$

in the limit, used here throughout, that the shock velocity ratio $U_1/U_2 = 4$; this is implied by our assumption that the shock is highly supersonic. The term ζ describes the resupply of secondary particles from other sources further upstream; $\zeta = 1$ denotes full resupply, i.e., no net loss, and $\zeta = 0$ is for no resupply.

These processes apply to the number of energetic secondaries, which is given by

$$C_{ep} \int \gamma_{ep}^{-22/9}\, d\gamma_{ep}, \tag{9}$$

where the integration limits are $\gamma_{ep1} \approx 200$ and $\gamma_{ep2} \gg \gamma_{ep1}$. We concentrate on the number of secondary particles, since further acceleration can not change this number, but modifies the spectrum. This can thus be written as

$$F \;=\; \frac{9}{13}\, C_{ep}\, \gamma_{ep1}^{-13/9}. \tag{10}$$

Replacing the radius r with the corresponding time dependence we have

$$r_{14} \;=\; 6\,10^{-6}\,(U_{1,-2} + V_{W,-2})\,t, \tag{11}$$

we have with

$$\begin{aligned} A \;=& 1.18\,10^{14}\,\eta_{p,-1}\, f_{\Delta} \\ & (\frac{\dot{M}_{-5}}{V_{W,-2}})^2\, \frac{1}{U_{1,-2}^2}\, \frac{1}{(1+V_W/U_1)^4}, \end{aligned} \tag{12}$$

the balance equation

$$\frac{dF}{dt} \;=\; \frac{A}{t^4} \,-\, \epsilon\,\frac{F}{t}, \tag{13}$$

where

$$\epsilon \;=\; 2 + \frac{1-\zeta}{1+V_W/U_1}. \tag{14}$$

Obviously, we have $2 \le \epsilon \le 3$; the limit of $U_1/V_W \gg 1$ and $\zeta = 0$ corresponds to $\epsilon = 3$. The integration yields

$$F \;=\; \frac{1}{3-\epsilon}\, \frac{A}{t_o^3}\, ((\frac{t_o}{t})^{\epsilon} \,-\, (\frac{t_o}{t})^3), \tag{15}$$

for $\epsilon \neq 3$ and

$$F \;=\; \frac{A}{t^3}\, \ln \frac{t}{t_o}, \tag{16}$$

for $\epsilon = 3$.

Now translating this expression back into a radial dependence we obtain

$$\begin{aligned} F \;=& 2.55\,10^{-2}\, \frac{1}{r_{14,o}^3}\, ((\frac{r_o}{r})^{\epsilon} \,-\, (\frac{r_o}{r})^3)\, \frac{1}{3-\epsilon} \\ & f_{\Delta}\, \eta_{p,-1}\, (\frac{\dot{M}_{-5}}{V_{W,-2}})^2\, U_{1,-2}\, \frac{1}{1+V_W/U_1}, \end{aligned} \tag{17}$$

and a corresponding expression in the two cases of $\epsilon \neq 3$ and $= 3$.

¿From this expression we can derive an equivalent value of $\eta_{ep}^{\star}$ which represents the energy of this population which we derive from observations ignoring the lower energy cutoff. The true energy content is lower by about a factor of 15 because of the low energy cutoff (for $\gamma_{ep,eff} = 200$). Using $\gamma_{ep,eff} = \gamma_{ep,1} = 200$ and $f_{\Delta} = 1.4$ this corresponds to an equivalent efficiency for electron/positron injection of

$$\begin{aligned} \eta_{ep}^{\star} \;=& 3.5\,10^{-4}\, \frac{1}{r_{14,o}}\, ((\frac{r_o}{r})^{\epsilon-2} \,-\, \frac{r_o}{r})\, \frac{1}{3-\epsilon} \\ & \eta_{p,-1}\, (\frac{\gamma_{ep,eff}}{200})^{13/9}\, (\frac{\dot{M}_{-5}}{V_{W,-2}})\, \frac{1}{U_{1,-2}}\, \frac{1}{1+V_W/U_1}, \end{aligned} \tag{18}$$

and again a corresponding expression in the two cases for the value of ϵ. This is, of course, only a good approximation as long as $\gamma_{ep,eff} \gg 1$.

The newly injected electrons and positrons are also subject to local energy gain and losses, which flatten their spectra to an index of $-7/3$ with the same low energy cutoff (see Drury 1983, section 2.3.2, with an added integration over the various source energies). As a consequence the numerical factors above change only slightly.

In the case that particle interaction is strong initially, say when the shock is close to the material of the accretion disk, then the formulae above change in an obvious way. In the balance equation the term corresponding to the newly created particles is zero and only an initial population exists which is slowly being diminished. There is an initial equivalent efficiency and thereafter it changes radially as

$$\eta_{ep}^{\star} \;=\; \eta_{ep,o}^{\star}\, (\frac{\gamma_{ep,eff}(r)}{200})^{13/9}\, (\frac{r_o}{r})^{\epsilon-2}. \tag{19}$$

In the case that there is a continuous or quasi-periodic resupply of energy to the population of secondary particles $\zeta \approx 1$, this means simply that $\eta_{ep}^{\star} = \eta_{ep,o}^{\star}$ where $\eta_{ep,o}^{\star}$ can approach the energy density of primary particles $\eta_{ep,o} \approx \eta_p$. A limit is $\gamma_{ep,eff}(r) = const \approx \gamma_{ep,1}$.

The induced numerical value for $\eta_{ep}^{\star}$ has to be compared with data. Therefore we have to ask three questions: First, can we explain the estimated value of η_e of order 10^{-6} for low velocity shocks in OB and WR stars, can we interpret the value of about 0.1 in SN-wind shocks, and can we at the same time interpret the value required by the observations of GK Per, of order nearly unity? This will then also give information on what to predict in secondary/primary ratio for high energy electrons. In order to do this we need to consider first the injection of protons.

3.2. Injection of energetic protons

3.2.1. The perpendicular case

Therefore we have to discuss the injection for protons (and nuclei), since we need to derive a physical theory for the value of r_o, where the protons start getting injected efficiently into the acceleration process (see Bell 1978a, b, Drury 1983). Consider a proton in the post-shock thermal tail of the Maxwellian distribution. In many papers Ellison and collaborators have shown that injection from the thermal tail downstream is possible (see, e.g., Ellison et al. 1990, Jones & Ellison 1991). We assume that a substantial population of such particles is built up.

We first consider the case where the unperturbed magnetic field is nearly parallel to the shock front; this case is valid over most of 4π for a spherical shock going through a Parker wind in its limiting configuration. In a Parker wind there is a polar cone region, where the magnetic field configuration is radial, and thus is perpendicular to the shock front. We consider this second case in the following subsection.

Now we ask the question: Can the injection of particles be maintained to keep on producing the energetic particle population? Consider for the sake of an example the case of a proton: Such a proton is subject most of all to two-body encounters with the thermal electrons, also simply referred to as ionization losses. The slow and steady energy gain from Fermi acceleration including drifts is hindered when the energy loss during one acceleration cycle is equal to or larger than the energy gain per cycle. The rate of energy loss is given in, e.g., Nath & Biermann (1993), and this rate has to be multiplied by the residence time in order to obtain the loss per cycle. In the subrelativistic regime the change in velocity βc can be written as

$$(\Delta\beta)_{loss} \;=\; 1.02\,10^{-3}\,(\frac{\dot{M}_{-5}}{V_{W,-2}})\,\frac{1}{U_{1,-2}^{3}}\,r_{14}^{-1}, \tag{20}$$

where we have used a factor of $1.3621\, m_p$ between mass density and hydrogen density and a factor of 1.181 between hydrogen density and electron density, valid for a fully ionized gas at cosmic abundances (Schmutzler 1987).

The gain per cycle in Fermi acceleration can be written in the subrelativistic limit as $(\Delta\beta)_{gain} = 10^{-2}\, U_{1,-2}$. Putting now gain and loss equal gives a lower limit for the radius, where shock acceleration can be sustained, r_o:

$$r_{o,14} \;=\; 0.10\,(\frac{\dot{M}_{-5}}{V_{W,-2}})\,\frac{1}{U_{1,-2}^{4}}. \tag{21}$$

Putting this back into the expression for the equivalent efficiency $\eta^{\star}_{ep}$ we obtain for $\epsilon \neq 3$

$$\begin{aligned}\eta^{\star}_{ep} \;=& 4.8\,10^{-4}\,((\frac{r_o}{r})^{\epsilon-2} - \frac{r_o}{r})\\ &(\frac{\gamma_{ep,eff}}{200})^{13/9}\,\eta_{p,-1}\,U_{1,-2}^{3}\,\frac{1}{1+V_W/U_1},\end{aligned} \tag{22}$$

and correspondingly for $\epsilon = 3$, where we have also included now the small correction for secondary acceleration of the secondary particles.

3.2.2. The parallel case

A contrast to the picture above is injection in the polar cone region, because there the magnetic field is predominantly radial already in its unperturbed stage. In the injection argument this means that we have to replace the residence time obtained from the concept of fast turbulent convection with a residence time derived from a turbulent wave field of waves parallel to the magnetic field.

The residence time (see, e.g., Drury 1983) is given by

$$\tau_{res} \;=\; \frac{4\kappa}{U_1 \beta c}, \tag{23}$$

where κ is the scattering coefficient, β is the particle velocity in units of the speed of light c, and U_1 is again the shock velocity. In the limit of strong turbulence at all relevant wavenumbers the scattering coefficient is given by

$$\kappa \;=\; \frac{1}{3}\,\frac{\beta m_p c^2}{eB(r)}\,\beta c, \tag{24}$$

where $B(r)$ is the radial magnetic field, dominant in the polar cone region region. We use here the nonrelativistic limit. From Parker's wind theory we have for the polar cone region, that

$$B(r) \;=\; 3\,10^{-3}\,\mathrm{Gauss}\,B_{0.5}\,\frac{V_W}{\Omega R_s}\,\frac{R_{s,11}}{r_{14}^{2}}, \tag{25}$$

where Ω is the angular rotation rate of the star, V_W is again the wind velocity, and $R_{s,11}$ is the radius of the star in units of 10^{11} cm. The magnetic field topology changes from a predominantly radial configuration near the equator to an increasingly tangential configuration at the radius given by V_W/Ω. As a consequence the residence time can be written in this limit as

$$\tau_{res} \;=\; 4.6\,\mathrm{sec}\,\frac{\beta}{B_{0.5} U_{1,-2}}\,\frac{\Omega R_s}{V_W}\,\frac{1}{R_{s,11}}\,r_{14}^{2}. \tag{26}$$

This time is so short because we use the extreme limit of the Larmor radius of the particles for the characteristic length of the transport.

The loss against interaction with the post-shock hot electrons is the most effective interaction, and peaks at that velocity for the particles when the protons have the same velocity as the heated thermal electrons. As before we use post-shock parameters for the loss arguments. Thus the interaction is maximized at $\beta = 0.23\, U_{1,-2}$. The interaction leads then to a loss of momentum $\Delta\beta$ equal to the gain from the Lorentz transformation of a particle going through the shock and getting scattered back at the condition

$$2.44\,10^{-6}\,\frac{\dot{M}_{-5}}{V_{W,-2}}\,\frac{1}{U_{1,-2}^{3}}\,\frac{\Omega R_s}{V_W}\,\frac{1}{R_{s,11}} \;=\; 1, \tag{27}$$

which is *independent* of radius; this is because the quadratic dependence of density and magnetic field in the polar cone region cancel here. If this condition is met, then the injection of energetic protons is hindered, and secondaries cannot be produced.

3.3. Application to stars

3.3.1. OB and WR stars

First, let us consider the normal OB and WR stars, where we have argued (CR II, and Biermann 1995) that η_e is of order $10^{-6\pm1}$.

It is clear that for ordinary parameters for OB and WR stars the condition derived above, eq. (27), is never met. One can show analoguously that ionization losses and pp-interaction cannot readily limit particle acceleration in the polar cone region.

This entails that injection of secondaries from pp-collisions may start quite close to the star, where densities are high. The radial behaviour of $\eta^{\star}_{ep}$ is estimated from our expressions earlier with $\epsilon \approx 0.5$:

$$\begin{aligned} \eta^{\star}_{ep} \; &= 5.5\,10^{-3}\,\frac{1}{R_{s,11}}\,(\frac{R_{s,11}}{r_{14}})^{1/2} \\ &\eta_{p,-1}\,(\frac{\gamma_{ep,eff}}{200})^{13/9}\,(\frac{\dot{M}_{-5}}{V_{W,-2}})\,\frac{1}{U_{1,-2}}, \end{aligned} \tag{28}$$

suggesting that secondaries *do not* play a dominant role in the radio emission of OB and WR stars; the number is too small because it refers *only* to the polar cone region. Inverse Compton losses further diminish any role of these secondaries.

The critical Alfvénic Mach number for shocks to inject primary electrons into an acceleration process in a shock is in the range of 3 to 30 - the value is highly uncertain at present (see paper CR III). We estimate the equatorial Alfvénic Mach number of shocks in the winds of OB and WR stars to be of order 0.3. Hence the angular range of electron injection is limited by $\theta_{cone} \approx 0.01$ to 0.1. Using then the implied conal area which participates in the radio emission, and the latitude dependence of the magnetic field of the Parker model wind, we arrive at the overall efficiency, i.e. that efficiency which we infer from observations ignoring the angular limitation. This number is then in the range 10^{-6} to 10^{-8} as required by the observations.

Our conclusion here then is that primary injection in a polar cone can explain the low apparent efficiency of the nonthermal radio emission in OB and WR stars. We emphasize that we consider single stars here. Given sufficient flux density, this conal restriction may be observable with VLBI.

3.3.2. Radio supernovae

Second, we can ask what is expected for radio supernovae: Here we likely have $\epsilon = 3$, $U_{1,-2} = 3$. The observed radio supernovae all except 1987A seem to have exploded into red giant winds with low velocity with $V_{W,-2} \approx 0.01$. It is easy to see that the radio emission from radio supernovae is fully consistent with all energetic electrons being primarily accelerated electrons which dominate by about two orders of magnitude or even more over the secondary electrons/positrons. However, when the supernova shock hits the surrounding shell that the steady wind often builds up over the lifetime of the star, then substantial secondary particle production takes place, which dominates over the earlier history of the shock running through the wind (see, e.g., Nath & Biermann 1994). We will discuss cosmic ray electrons elsewhere (paper CR VI, in prep.).

3.3.3. GK Per

Last, let us consider the case of the nova GK Per: Optical data on the emitting mass, usually identified with the ejected mass, (Pottasch 1959) give a mass of $7.0\,10^{-5}\,\mathrm{M}_{\odot}$. We identify this with the mass in the shocked shell of the wind material, under the premise that the ejecta caused a shock to run through a pre-existing wind. With this notion we obtain for $\dot{M}_{-5}/V_{W,-2}$ a value of $0.22\,f_{\rho}$. However, nova shells are not spherically symmetric and so the spherically averaged mass in the wind shell is estimated to be approximately three times higher (Seaquist et al. 1989). We will use this higher value in the following, and use f_{ρ} to account for any further differences. Using such an approach the uncertainty in r_o becomes so large, that we keep this radius in the expression and so to a fair approximation we have for GK Per

$$\begin{aligned} \eta^{\star}_{ep} \; &= 2.3\,10^{-3}\,\frac{1}{r_{o,14}^{3-\epsilon}}\,\frac{1}{r_{14}^{\epsilon-2}} \\ &(\frac{\gamma_{ep,eff}}{200})^{13/9}\,\eta_{p,-1}\,f_{\rho}\,\frac{1}{U_{1,-3}}. \end{aligned} \tag{29}$$

The lowest reasonable limit for the injection radius is clearly the size of the binary system, or the inner region of the accretion disk, giving $r_{o,14} > 4\,10^{-3}$ and $r_{o,14} > 4\,10^{-4}$. With the full limitation of the observed radio emission to a cone and no allowance for clumping in the magnetic field we find that the efficiency can indeed be as high as required by the observations, under the condition that the shock speed is smaller than the Alfvén velocity at the equator.

If we try to find solutions where there is appreciable secondary production in the wind, we fail; the main injection, in this picture, has to arise from the inital environment, at the inner edge of the accretion disk.

The source parameters derived here suggest that secondaries from hadronic interactions, i.e. p-p interactions here, give an equivalent injection efficiency between $\approx 10^{-2}$ and 1. All this implies, that $\gamma_{ep,eff}$ is approximately constant, which leads to a solution close to the case $\eta^{\star}_{ep} \approx$ *const* and maximal, and ϵ very close to a value of 2. This in turn implies either a slow shock ($V_W \gg U_1$) or substantial resupply of secondaries from upstream ($\zeta \approx 1$).

Hence we have found a consistent, albeit speculative picture that explains the radio emission of GK Per as produced by secondary electrons/positrons, with a theory which also gives acceptable estimates for OB and WR stars, as well as radio supernovae, where the *standard* acceleration from the thermal pool is probably dominant, but restricted to the polar cone as an injector for OB and WR stars.

4. Consequences for other sources and other wavelengths

4.1. Other stellar binary systems

The model implies copious pp-interaction at the beginning of the shock travelling through the wind. A consequence is both a power law continuum from π^o decay as well as an annihilation line from secondaries. In nova Muscae Chen et al. (1993) have observed a 511 keV annihilation line, which they argue arises from a region near the inner edge of an accretion disk. In the same nova Goldwurm et al. (1992) describe observations of a γ-continuum with slope -2.38 ± 0.05, consistent with a primary spectrum of protons of slope near $-7/3$.

4.2. Other radio sources with related characteristics

There are a number of other radio sources which appear to show properties consistent with the picture which we propose. Secondaries have been discussed to explain other features in the spectra of radio sources (see, e.g., Klemens 1987, Biermann & Strittmatter 1987, Mannheim 1993a, 1993b).

Klemens (1987) described the X-ray emission of the M87 jet successfully with the concept that secondaries from hadronic interaction give rise to synchrotron X-ray emission.

The Galactic center source shows a spectrum which rises approximately as $\nu^{1/3}$ through the radio range; it is not clear at this stage whether this spectral behaviour is due to optical thickness effects or due to another process such as discussed here. The Galactic center source has been discussed elsewhere (Falcke 1995), following our earlier modelling (Falcke et al. 1993, Falcke & Biermann 1995, Falcke et al. 1995).

The most prominent example among radio galaxies is Cyg A (Muxlow et al. 1988). The radio emission of the lobes shows a low frequency turnover near 200 MHz which then can be connected with an estimate of the relevant magnetic field to a minimum energy of the electron distribution of about $\gamma_1 \simeq 350 \pm 50$. There is evidence that radio galaxies in general tend to flatten towards low frequency (Laing & Peacock 1980, Mangalam & Gopal-Krishna 1994), which may be related to a low energy cutoff in the electron distribution; the effect should be strong only at very low radio frequencies due to the estimated low magnetic field strengths in radio galaxies.

5. Is there an alternative?

Where is the main weakness of the model proposed? The key is clearly the argument that hadronic secondaries are able to account for the spectrum. Therefore, in this section we propose to ask whether primary injection and acceleration can also produce the pattern of radio polarization, radio emission strength, radio structure and radio spectrum.

The radio polarization has been argued to arise from the instability of a cosmic ray mediated shock (see paper CR I, CR II and Biermann 1995). The argument on secondary or primary injection is indifferent to this, since we use primary protons to drive the instability.

The radio emission strength could be explained by invoking little or no magnetic clumping and just using the decrease of total flux from the geometry of the underlying magnetic field. Since the magnetic field strength in a Parker wind decreases as $\sin\theta$ towards the poles, the total radio emission is reduced by a factor of one to two orders of magnitude, depending upon which cutoff angle we use. This entails a corresponding increase in the implied efficiency to about the maximum possible. The cutoff angle would still arise from the limiting condition on injection, and hence correspond to a lower magnetic field strength than used above. This runs into the problem that the efficiency may then have to be increased beyond any reasonable level.

The radio structure would derive from the same argument as before, the drift asymmetry in the accelerated particle population in the two hemispheres (see paper CR I, CR II and Biermann 1995).

The radio spectrum would also be easy to accomodate in the concept that the explosion advances into the interstellar medium (paper CR III); however, the spatial asymmetry is then difficult to interpret.

Finally, for the low frequency cutoff we would require a new and rather difficult explanation, like foreground absorption, an extremely clumpy absorbing medium, or something else. Seaquist et al. (1989) discussed all likely possibilities, and found no other reasonable explanation. Therefore the radio observation of the low frequency turnover is the key observation on which everything rests. A very low frequency spectrum of GK Per would be decisive to settle the interesting question on the role of hadronic secondaries, and thus on the presence of accelerated protons in a specific radio source.

6. Conclusion

We have tested a model proposed earlier to account for the spectrum, particle energies and chemical composition of cosmic rays with the observations of the nonthermal radio emission from the nova GK Per. We obtain a consistent picture implying a pre-existing strong stellar wind. Such a strong wind can strongly influence the evolution of a low mass binary like GK Per due to mass and angular momentum loss from the system (see, e.g., Kim et al. 1992, Iben 1995).

We interpret the radio spectrum of GK Per as resulting from hadronic secondary electrons/positrons, which, in the optically thin case, give a characteristic radio spectrum with a spectral index of $+1/3$ below a maximum and, for a strong shock in a wind slow compared to the shock speed, of ≈ -0.7 above the maximum. We argue that such a radio spectrum is a unique characteristic for hadronic interactions. We can account for the observed radio emission, its spectrum including the low frequency cutoff, its radio polarization properties, geometric shape and its luminosity.

We have applied the concepts developed to OB and Wolf Rayet stars, as well as radiosupernovae, and have been able to verify that the efficiencies of injection implied by the observations can be readily interpreted quantitatively, however, with primary injection. One consequence is that the radio emission in OB and Wolf Rayet stars is from a polar cone, just as in GK Per, but restricted much more in angle.

We have shown, that the radio emission properties of the old nova GK Per can consistently be interpreted in the context of our proposed model for the origin of cosmic rays, and have made a small step in the direction of accounting for secondaries from nucleus - nucleus interaction in the populations of energetic particles. We point out the key radio observation to confirm the model proposed, an accurate very low frequency spectrum of GK Per.

Acknowledgements. The authors appreciate the help of Dr. W. Duschl in elucidating the role and physics of cataclysmic variables and novae; he was an important partner in starting this paper. PLB wishes to acknowledge helpful discussions with Drs. K. Daum, Gopal Krishna, C. Jarlskog, H. Lesch, G. Mann, B.B. Nath, M. Niemeyer, S.P. Reynolds and E.R. Seaquist. Critical comments by the referee helped to bring this paper into focus. H. Falcke was supported by the DFG under grant Bi 191/9.

References

Abbott, D.C., Bieging, J.H., Churchwell, E., Torres, A.V.: 1986 Astrophys. J. 303, 239
Baars, J.W.M., Genzel, R., Pauliny-Toth, I.I.K., Witzel, A.: 1977 Astron. & Astroph. 61, 99
Band, D. et al. 1993: Astrophys. J. 413, 281
Bell, A.R.: 1978a Monthly Not. Roy. Astr. Soc. 182, 147
Bell, A.R.: 1978b Monthly Not. Roy. Astr. Soc. 182, 443
Bieging, J.H., Abbott, D.C., Churchwell, E.B.: 1989 Astrophys. J. 340, 518
Biermann, P.L., Strittmatter, P.A.: 1987 Astrophys. J. 322, 643
Biermann, P.L.: 1993 Astron. & Astroph. 271, 649 (paper CR I)
Biermann, P.L., Cassinelli, J.P.: 1993 Astron. & Astroph. 277, 691 (paper CR II)
Biermann, P.L., Strom, R.G.: 1993 Astron. & Astroph. 275, 659 (paper CR III)
Biermann, P.L., Gaisser, T.K., Stanev, T.: 1995 Phys. Rev. D (in press)
Biermann, P.L.: 1995 in "Cosmic winds and the Heliosphere", Eds. J.R.Jokipii et al., Univ. of Arizona Press, Tucson, AZ, (in press)
Chen, W., Gehrels, N. Cheng, F.H.: 1993 Astrophys. J. Letters 403, L71
Dickel, J.R., Breugel, W.J.M. van, Strom, R.G.: 1991 Astron. J. 101, 2151
Drury, L.O'C.: 1983 Rep.Prog.Phys. 46, 973
Ekspong, A.G., Yamadagni, N.K., Bonnevier, B.: 1966 Phys. Rev. Letters 16, 664
Ellison, D.C. et al.: 1990 Astrophys. J. 352, 376
Falcke, H., Mannheim, K., Biermann, P.L.: 1993 Astron. & Astroph. 278, L1
Falcke, H., Biermann, P.L.: 1995 Astron. & Astroph. 293, 665
Falcke, H., Malkan, M.A., Biermann, P.L.: 1995 Astron. & Astroph. (in press)
Falcke, H.: 1995 in IAU Sympos. 169 "Unsolved problems of the Galaxy", Ed. L. Blitz, Kluwer, Dordrecht (in press)
Ginzburg, V.L., Syrovatskii, S.I.: 1964 "The origin of cosmic rays", Pergamon Press, Oxford
Goldwurm, A. et al.: 1992 Astrophys. J. Letters 389, L79
Gould, R.J., Burbidge, G.R.: 1968 Handbuch der Physik 46/2, p. 265
Hayakawa, S., Okuda, H.: 1962 Progr. Theoret. Phys. 28, 517
Hjellming, R.M.: 1990 in "Physics of classical novae", Eds. A. Cassatella, R. Viotti, Lecture Notes in Physics No. 369, Springer, Berlin, p.169
Iben, I. jr.: 1995 Phys. Rep. 250, 1
Jokipii, J.R., Levy, E.H., Hubbard, W.B.: 1977 Astrophys. J. 213, 861
Jones, F.C., Ellison, D.C.: 1991 Space Sc. Rev. 58, 259
Kim, S.-W., Wheeler, J.C., Mineshige, S.: 1992 Astrophys. J. 384, 269
Klemens, Y.: 1987 Ph.D. Thesis University of Bonn
Laing, R.A., Peacock, J.A.: 1980 Monthly Not. Roy. Astr. Soc. 190, 903
MacFarlane, J.J., Cassinelli, J.P.: 1989 Astroph. J. 347, 1090
Mangalam, A.V., Gopal Krishna: 1994 Monthly Not. Roy. Astr. Soc. (submitted)
Mannheim, K.: 1993a Astron. & Astroph. 269, 67
Mannheim, K.: 1993b Phys. Rev. D 48, 2408

Muxlow, T.W.B., Pelletier, G., Roland, J.: 1988 Astron. & Astroph. 206, 237
Nath, B.B., Biermann, P.L.: 1993 Monthly Not. Roy. Astr. Soc. 265, 241
Nath, B.B., Biermann, P.L.: 1994 Monthly Not. Roy. Astr. Soc. 270, L33
Niemeyer, M.: 1995 Ph.D. Thesis University of Bonn
Pottasch, S.R.: 1959 Ann. d'Astroph. 22, 412
Rachen, J.P., Biermann, P.L.: 1993 Astron. & Astroph. 272, 161 (paper UHE CR I)
Rachen, J.P., Stanev, T., Biermann, P.L.: 1993 Astron. & Astroph. 273, 377 (paper UHE CR II)
Reynolds, S.P., Chevalier, R.A.: 1984 Astrophys. J. Letters 281, L33
Romanova, M.M., Lovelace, R.V.E., Bisnovatyi-Kogan, G.S.: 1994 Monthly Not. Roy. Astr. Soc. (submitted)
Schmutzler, T. 1987 Ph.D. Thesis University of Bonn
Seaquist, E.R., Bode, M.F., Frail, D.A., Roberts, J.A., Evans, A., Albinson, J.S.: 1989 Astrophys. J. 344, 805
Sikora, M., Kirk, J.G., Begelman, M.C., Schneider, P.: 1987 Astrophys. J. Letters 320, L81
Stanev, T., Biermann, P.L., Gaisser, T.K.: 1993 Astron. & Astroph. 274, 902 (paper CR IV)
Stephens, S.A., Bhadwar, G.D.: 1981 Astroph. & Space Sci. 76, 213
Stecker, F.W.: 1971 "Cosmic Gamma Rays", NASA-book

This article was processed by the author using Springer-Verlag TEX AA macro package 1989.