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The imprint of Gould's Belt on the local cosmic-ray electron spectrum

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Abstract. In a recent paper Pohl and Esposito (1998) demonstrated that if the sources of cosmic-rays are discrete, as are Supernova Remnants (SNR), then the spectra of cosmic-ray electrons largely vary with location and time and the locally measured electron spectrum may not be representative of the electron spectra elsewhere in the Galaxy, which could be substantially harder than the local one. They have shown that the observed excess of γ-ray emission above 1 GeV can in fact be partially explained as a correspondingly hard inverse Compton component, provided the bulk of cosmic-ray electrons is produced in SNR.

As part of a program to model the Galactic γ-ray foreground we have continued the earlier studies by investigating the impact of the star forming region Gould's Belt on the local electron spectrum. If the electron sources in Gould's Belt were continous, the local electron spectrum would be slightly hardened. If the electron sources are discrete, which is the more probable case, the variation in the local electron spectrum found by Pohl & Esposito persists.

1 The local cosmic-ray electron spectrum

The recent detections of non-thermal X-ray synchrotron radiation from the supernova remnants SN1006 (Koyama et al., 1995), RX J1713.7-3946 (Koyama et al., 1997), IC443 (Keohane et al., 1997; Slane et al., 1999), Cas A (Allen et al., 1997), and RCW86 (Borkowski et al., 2001) and the subsequent detections of SN1006 (Tanimori et al., 1998), RX J1713.7-3946 (Muraishi et al., 2000), and Cas A (Aharonian et al., 2001) at TeV energies support the hypothesis that at least Galactic cosmic-ray electrons are accelerated predominantly in SNR.

The Galactic distribution and spectrum of cosmic-ray electrons are intimately linked to the distribution and nature of their sources. Supernovae and hence their remnants are transient features, which happen stochastically in space and time. Therefore steady-state models of cosmic-ray electron propagation in the Galaxy may be inadequate and time-dependent transport calculation seem to be required.

Because effects of the discreteness of sources show up only at higher particle energy, at which the electron energy loss time is short, we may describe the propagation of cosmic-ray electrons at energies higher than a few GeV by a simplified, time-dependent transport equation

$$\frac{\partial N}{\partial t} - \frac{\partial}{\partial E}(bE^2\,N) - D\,E^a\,\nabla^2 N = Q \qquad (1)$$

where we consider continous energy losses by synchrotron radiation and inverse Compton scattering, a diffusion coefficient $D\,E^a$ dependent on energy, and a source term Q. The Green's function for this problem can be found in the literature (Ginzburg and Syrovatskii, 1964).

$$G = \frac{\delta\left(t - t' + \frac{E-E'}{b\,E\,E'}\right)}{bE^2\ (4\pi\,\lambda)^{3/2}}\ \exp\left(-\frac{(r-r')^2}{4\,\lambda}\right) \qquad (2)$$

with

$$\lambda = \frac{D\ \left(E^{a-1} - E'^{a-1}\right)}{b\,(1-a)} \qquad (3)$$

In case of discrete sources the injection term Q is a sum over all sources. For an individual source showing up at time t_0 and injecting for a time period τ we can write

$$Q_i = q_0\,E'^{-s}\,\delta(r')\,\Theta(t'-t_0)\,\Theta(t_0+\tau-t') \qquad (4)$$

Without loss of generality we can set $t=0$ and obtain

$$N = q_0\,E^{-s}$$
$$\times \int_{-\frac{1}{bE}}^{0} dt'\ \frac{\Theta(t'-t_0)\,\Theta(t_0+\tau-t')}{(4\pi\Lambda)^{3/2}\ (1+bEt')^{2-s}}\ \exp\left(-\frac{r^2}{4\Lambda}\right) \qquad (5)$$

where

$$\Lambda = \frac{D\,E^{a-1}}{b\,(1-a)}\ \left(1-(1+bEt')^{1-a}\right) \qquad (6)$$

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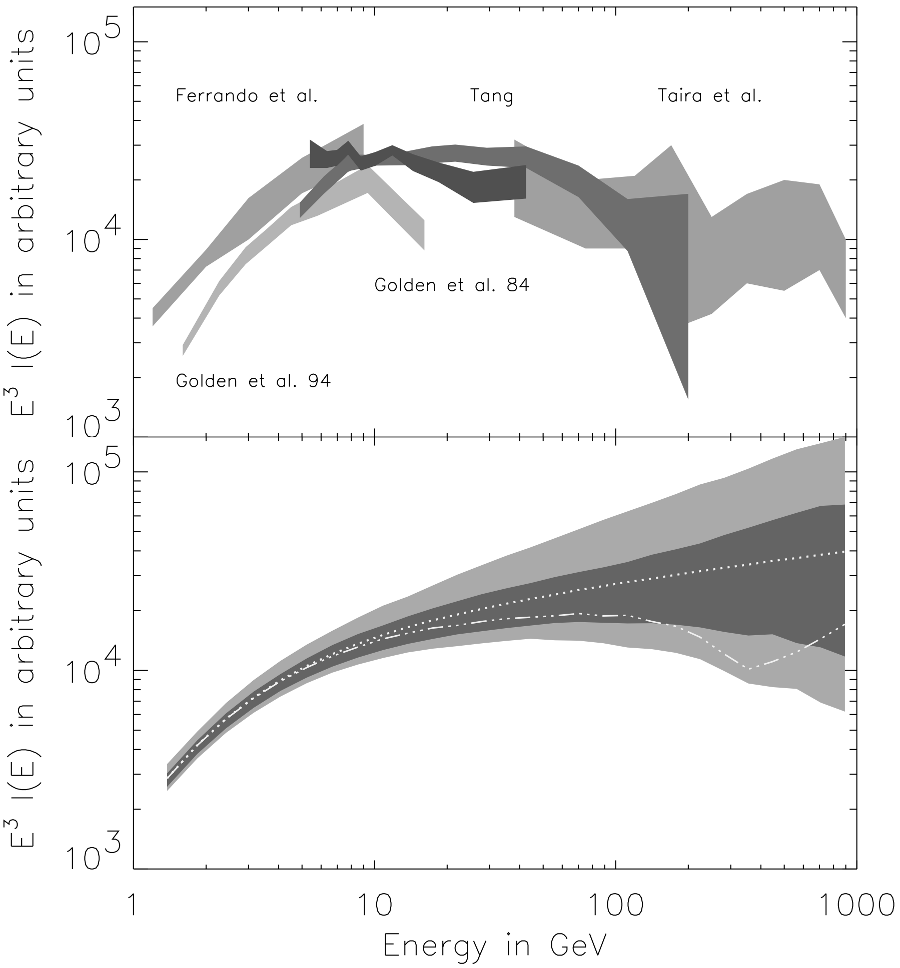

Fig. 1. The locally observed electron spectrum in the upper panel compared with the range of possible spectra in the calculation of Pohl and Esposito (1998) for a homogeneous population of sources in the Galactic disc with an initial spectral index of $s = 2.0$ at the sources. For each experiment the 1 σ uncertainty range is indicated by a grey-shaded band which connects the data points at the mean energies of the corresponding energy bins. The range of possible spectra in our model is given by the grey-shaded bands in the lower panel. At each energy the locally observed spectra will be in the dark grey shaded region during 68% of the time, and during 95% of the time they will be within the light grey shaded region. The white dash-dotted line shows one of 400 random spectra as a particular example of what may be observed. The white dotted line indicates the time-averaged spectrum.

and r is the distance between source and observer. N is the contribution to the local electron spectrum provided by a single source (SNR) at distance r which is (was) injecting electrons for a time period τ starting at t_0. The local spectrum of electrons can now be obtained by summing the contributions from all individual sources. The actual location and explosion time of a supernova is random. Therefore we can only use a random number generator to calculate possible local electron spectra, given a spatial and temporal probability distribution for the occurence of supernovae, and thus determine the probability distribution of the local cosmic-ray electron flux at each energy.

The spatial distribution of sources modifies the local electron spectrum, while the randomness in time induces a time variability in the local electron flux at higher energies, that stems from the fluctuations in the number of SNR within a certain distance and time interval. Thus the discreteness of sources does not only cause a cutoff in the electron spectrum, but makes it variable with time and thus unpredictable beyond a certain energy (Pohl and Esposito, 1998).

In Fig.1 we show the range of variability in comparison with the measured local electron spectrum for a homogeneous distribution of SNR in the Galaxy. The effect of solar modulation has been taken into account for all model spectra using a force-field parameter $\Phi = 400$ MeV (Gleeson and Axford, 1968). While in steady-state models the observed electron spectrum requires an electron source spectral index of $s = 2.4$, it is in the range of possible local spectra with $s = 2.0$ in the time-dependent calculation. This implies that the average electron spectrum in the Galaxy, e.g. probed by line-of-sight integrals of leptonic emission through the Galactic plane, can be much harder than would be deduced in steady-state models. Pohl & Esposito have shown that the observed excess of gamma ray emission above 1 GeV (Hunter et al., 1997) can in fact be explained as a correspondingly hard inverse Compton component. A cosmic-ray electron source spectral index $s = 2.0$ would also correspond to the average radio synchrotron spectral index $< \alpha >= 0.5$ in shell-type SNR (Green, 2001).

2 The imprint of Gould's Belt on the electron spectrum

In the earlier calculations the supernova rate per area was assumed uniform throughout the Galactic plane. In this paper we investigate the impact of a local, non-uniform SNR distribution on the local cosmic ray electron spectrum. The most

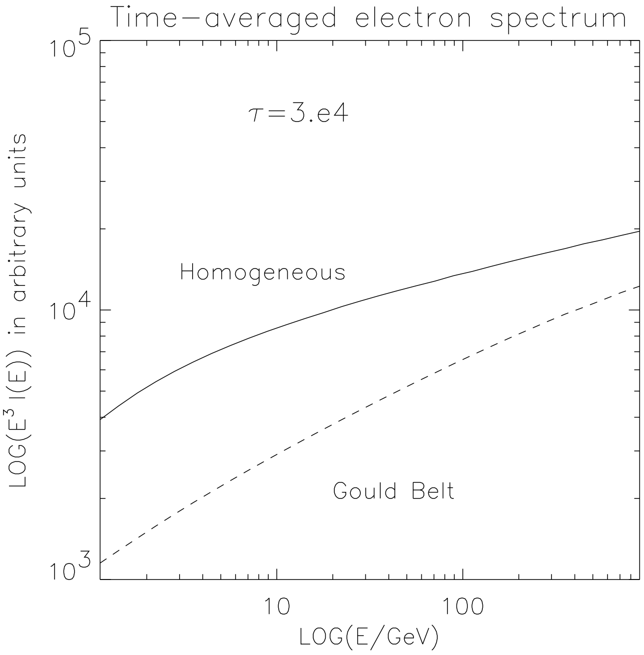

Fig. 2. The steady-state local electron spectrum for a homogeneous Galactic disc distribution of SNR in comparison with that for SNR in Gould's Belt, both with the same SN rate per area. Here the lifetime of SNR was assumed $\tau = 30000$ yrs.

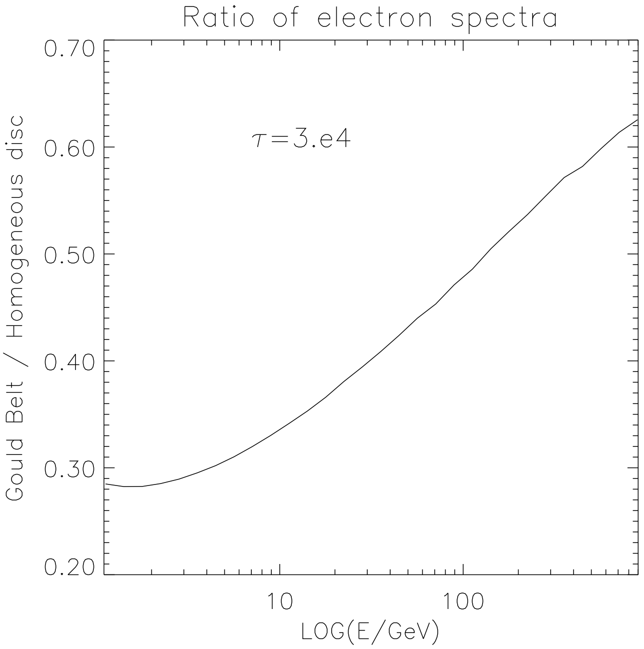

Fig. 3. The ratio of the steady-state local electron spectra for SNR in Gould's Belt and for a homogeneous Galactic disc distribution of SNR, both with the same SN rate per area.

prominent local star-forming region is Gould's Belt (Pöppel, 1997), an expanding disc-like region tilted at about 18∘ to the Galactic plane and about 600 pc in diameter, in which the supernova rate per area is three to five times higher than the Galactic rate at the solar circle (Grenier, 2000). Based on its stellar content the age of this structure can be estimated to be 30 to 40 Myr. Assuming the evolution of Gould's Belt to be entirely determined by kinematical effects following an initial explosive event, its expansion history can be modelled (Grenier and Perrot, 2001). This model can serve as a probability distribution of supernovae in space and time to be used in Eq.1 for the source term Q.

In Fig.2 and Fig.3 we show the results for the average (steady-state) local electron spectrum. At higher electron energies the radiative energy losses permit only local SNRs to contribute to the local electron flux. Thus a locally enhanced SNR rate is increasingly important with increasing electron energy. Consequently, the contribution of SNR in Gould's Belt has a slightly harder spectrum than that of Galactic disc distribution of SNR, as has the summed electron spectrum. The hard spectrum of electrons from the Gould's Belt SNR is entirely a geometrical effect. Here we have assumed that enhanced SN activity commences without delay in the regions which are over-run by the expanding front of Gould's Belt. In reality this may not be true, in which case the effect of Gould's Belt would be less than calculated here. We have also assumed that the SN rate per area is constant within the Belt disc.

We have then calculated the range of possible local electron spectra for the time-dependent case, shown in Fig.4 in comparison with that for a homogeneous Galactic disc distribution of SNR. The flux variability amplitude is marginally smaller for the Galactic disc distribution plus Gould's Belt, because in this case we expect more local SNR than in the earlier calculation, and therefore the relative width of the Poissonian distribution, which governs the variability amplitude, is smaller. At the same time the cosmic-ray electron source power per SNR required to sustain the observed local electron flux is slightly reduced to $\sim 60\%$ of the SNR source power in the old calculation.

3 Discussion

In this paper we have investigated the effect of Gould's Belt as a local system of enhanced star-forming and hence supernova activity on the local cosmic-ray electron spectrum under the assumption that the electron are solely produced in SNR. We have seen that on average the local electron spectra would be slightly harder than in the case of a homogeneous Galactic disc distribution of SNR. At the same time the variability induced by the discrete nature of SNR in space and time would be only marginally reduced compared with the case of homogeneously distributed SNR (Pohl and Esposito, 1998).

Consequently, the electron source spectra in SNR must be slightly softer by $\Delta s \simeq 0.07$ than previously thought. Hard electron source spectra and the correspondingly hard inverse Compton gamma-ray spectra have been discussed as a possible explanation of the excess of Galactic GeV γ-rays observed with EGRET. Our results do not rule out this hypoth-

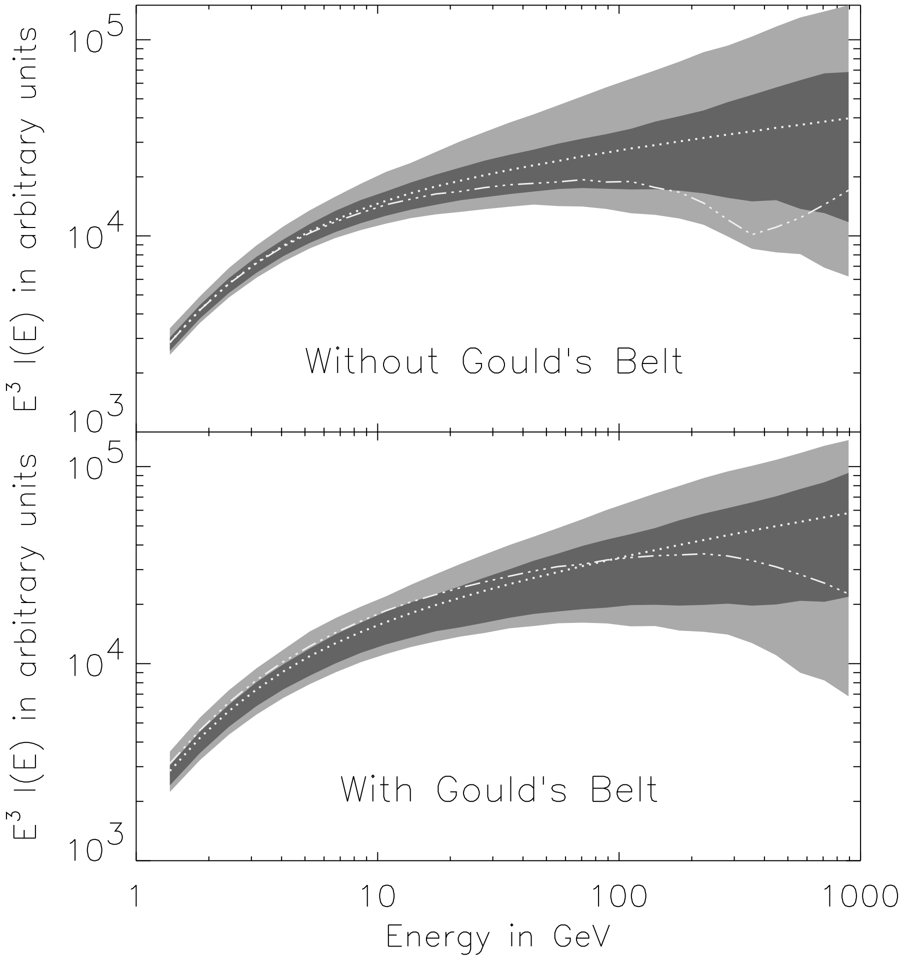

Fig. 4. The range of possible spectra for a homogeneous Galactic distribution of SNR (top, the same as in Fig.1) compared with the range obtained for a Galactic distribution plus Gould's Belt (bottom). The level of variability is marginally smaller in the Gould's Belt case.

esis, but certainly reduce the available parameter space for such models.

The conclusions presented here rely on the assumption that cosmic-ray electron are solely produced in SNR, as a consequence of which the local electron spectrum above 50 GeV may show deviations from power-law behaviour such as bumps and dents. New electron measurements in the energy range above 100 GeV are urgently required to possibly detect such spectral structures and thereby confirm an electron origin in discrete sources.

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