PAIR WINDS IN SCHWARZSCHILD SPACETIME WITH APPLICATION TO STRANGE STARS

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We present the results of numerical simulations of stationary, spherically outflowing, $e^\pm$ pair winds, with total luminosities in the range $10^{34} - 10^{42}$ ergs s$^{-1}$. In the concrete example described here, the wind injection source is a hot, bare, strange star, predicted to be a powerful source of $e^\pm$ pairs created by the Coulomb barrier at the quark surface. We find that photons dominate in the emerging emission, and the emerging photon spectrum is rather hard and differs substantially from the thermal spectrum expected from a neutron star with the same luminosity. This might help distinguish the putative bare strange stars from neutron stars.

1. Introduction

For an electron-positron ($e^\pm$) wind out-flowing spherically from a surface of radius $R$ there is a maximum pair luminosity, $L_{\text{max}}^{\pm} = 4\pi m_e c^3 R \Gamma^2 / \sigma_T \simeq 10^{36}(R/10^6\text{cm})^2 \text{ergs s}^{-1}$, beyond which the pairs annihilate significantly before they escape, where $\Gamma$ is the pair bulk Lorentz factor, and $\sigma_T$ the Thomson cross section. Recently we developed a numerical code for solving the relativistic kinetic Boltzmann equations for pairs and photons in Schwarzschild geometry. Using this we considered a spherically out-flowing, non-relativistic ($\Gamma \sim 1$) pair winds with injected pair luminosity $\tilde{L}_{\pm}$ in the range $10^{34} - 10^{42}$ ergs s$^{-1}$, that is $\tilde{L}_{\pm} \sim (10^{-2} - 10^0)L_{\text{max}}^{\pm}$ (Aksenov et al. 2003, 2004, 2005). While our numerical code can be more generally employed, the results presented in this paper are for a hot, bare, strange star as the wind injection source. Such stars are thought to be powerful (up to $\sim 10^{51}$ ergs s$^{-1}$) sources of pairs created by the Coulomb barrier at the quark surface (Usov 1998, 2001).

2. Formulation of the problem

We consider an $e^\pm$ pair wind that flows away from a hot, bare, unmagnetized, non-rotating, strange star. Space-time outside the star is described by Schwarzschild’s metric with the line element

$$ds^2 = -e^{2\phi} c^2 dt^2 + e^{-2\phi} dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2),$$

(1)

where $e^\phi = (1 - r_g/r)^{1/2}$ and $r_g = 2GM/c^2 \simeq 2.95 \times 10^5(M/M_\odot)$ cm.
We use the general relativistic Boltzmann equations for the pairs and photons, whereby the distribution function for the particles of type \( i \), \( f_i(p, \mu, r, t) \), satisfies

\[
\frac{e^{-\phi}}{c} \frac{\partial f_i}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \mu e^{\phi} \beta_i f_i \right) - \frac{e^{\phi}}{p^2} \frac{\partial}{\partial p} \left( p^3 \mu \beta_i f_i \right) - \frac{\partial}{\partial \mu} \left[ (1 - \mu^2) e^{\phi} \left( \frac{\beta_i}{\mu} - \frac{\beta_i}{r} \right) f_i \right] = \sum_q \left( \bar{\eta}^q_i - \chi^q_i f_i \right). \tag{2}
\]

Here, \( \mu \) is the cosine of the angle between the radius and the particle momentum \( p \), \( p = |p| \), \( \beta_e = v_e/c \), \( \beta_\gamma = 1 \), and \( v_e \) is the velocity of electrons and positrons. Also, \( \bar{\eta}^q_i \) is the emission coefficient for the production of a particle of type \( i \) via the physical process labelled by \( q \), and \( \chi^q_i \) is the corresponding absorption coefficient. The processes we include are listed in the following Table.

| Basic Two-Body Interaction | Radiative Variant |
|---------------------------|------------------|
| Møller and Bhaba scattering | Bremsstrahlung |
| \( ee \rightarrow ee \) | \( ee \leftrightarrow ee\gamma \) |
| Compton scattering | Double Compton scattering |
| \( \gamma e \rightarrow \gamma e \) | \( \gamma e \leftrightarrow \gamma e\gamma \) |
| Pair annihilation | Three photon annihilation |
| \( e^+ e^- \rightarrow \gamma \gamma \) | \( e^+ e^- \leftrightarrow \gamma \gamma \gamma \) |
| Photon-photon pair production | |
| \( \gamma \gamma \rightarrow e^+ e^- \) | |

3. Numerical results

For injected pair luminosity \( \tilde{L}_\pm \) higher than \( \sim 10^{34} \) ergs s\(^{-1} \), the emerging emission consists mostly of photons (see Fig. 1, left panel). This simply reflects the fact that in this case the pair annihilation time \( t_{\text{ann}} \sim (n_e \sigma T)/c \) is less than the escape time \( t_{\text{esc}} \sim R/c \). There is an upper limit to the rate of emerging pairs \( \dot{N}_e^{\text{max}} \sim 10^{43} \) s\(^{-1} \) (see Fig. 1, right panel).

As \( \tilde{L}_\pm \) increases from \( \sim 10^{34} \) to \( 10^{42} \) ergs s\(^{-1} \), the mean energy of emergent photons decreases from \( \sim 400 \) keV to 40 keV, as the spectrum changes in shape from that of a wide annihilation line to nearly a blackbody spectrum with a high energy (> 100 keV) tail (see Fig. 2).
Fig. 1. LEFT: The fractional emerging luminosities in pairs (dashed line) and photons (solid line) as functions of the injected pair luminosity, $\tilde{L}_\pm$. RIGHT: Number rate of emerging pairs as functions of $\tilde{L}_\pm$ (solid line). The case where gravity has been neglected is shown by the dashed line.

Fig. 2. LEFT: The energy spectrum of emerging photons for different values of $\tilde{L}_\pm$, as marked on the curves. The dashed line is the spectrum of blackbody emission. RIGHT: The mean energy of the emerging photons (thick solid line) and electrons (thin solid line) as a function of $\tilde{L}_\pm$. For comparison, we show as the dotted line the mean energy of blackbody photons for the same energy density as that of the photons at the photosphere. Also shown as the dashed line is the mean energy of the emerging photons in the case when only two particle processes are taken into account.

Acknowledgments

The research was supported by the Israel Science Foundation of the Israel Academy of Sciences and Humanities.

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