A sophisticated analysis of EGRET data has found evidence for gamma-ray emission from the galactic halo. I entertain the possibility that part of the EGRET signal is due to WIMP annihilations on the gamma-ray spectrum of the halo emission. I introduce a particle physics model with a suitable dark matter candidate that satisfies present observational and experimental constraints, and makes strict predictions on the gamma-ray spectrum of the halo emission.

Dixon et al. [1], in a sophisticated analysis of the EGRET gamma-ray data, have found evidence for gamma-ray emission from the galactic halo. Filtering the data with a wavelet expansion, they have produced a map of the intensity distribution of the residual gamma-ray emission after subtraction of an isotropic extragalactic component and of expected contributions from cosmic ray interactions with the interstellar gas and from inverse Compton of ambient photons by cosmic ray electrons. Besides a few “point” sources, they find an excess in the central region extending somewhat North of the galactic plane, and a weaker emission from regions in the galactic halo. They mention an astrophysical interpretation for this halo emission: inverse Compton of cosmic ray electrons distributed on larger scales than those commonly discussed and with anomalously hard energy spectrum.

I find it intriguing that the angular distribution of the halo emission resembles that expected from pair annihilation of dark matter WIMPs in the galactic halo, and moreover, that the gamma-ray intensity is similar to that expected from annihilations of a thermal relic with present mass density 0.1–0.2 of the critical density. Namely, the emission at $b \geq 20^\circ$ is approximately constant at a given angular distance from the galactic center except for a region around $(b, l) = (60^\circ, 45^\circ)$, correlated to the position of the Moon, and a region around $(b, l) = (190^\circ, -30^\circ)$, where there is a local cloud $(b$ and $l$ are the galactic latitude and longitude, respectively). Dixon et al. [1] argue against the possibility of WIMP annihilations on the base that direct annihilation of neutralinos into photons would give too low a gamma-ray signal. However most of the photons from WIMP annihilations are usually not produced directly but come from the decay of neutral pions generated in the particle cascades following annihilation.

In this letter I show that WIMP annihilation can account for both the intensity and the spatial distribution of the halo emission. A model independent analysis, although instructive (see Ref. [2]), would necessarily be vague. So to be concrete, I introduce a particle physics model with a suitable dark matter candidate that satisfies present observational and experimental constraints.

Consider a few GeV Majorana fermion in a model with an extended Higgs sector. The Higgs sector contains two Higgs doublets $H_1$ and $H_2$ and a Higgs singlet $N$. Let the Higgs potential be

$$V_{\text{Higgs}} = \lambda_1 \left( H_1^+ H_1 - v^2 \right)^2 + \lambda_2 \left( H_2^+ H_2 - v^2 \right)^2 + \lambda_3 \left| N^2 - v_N^2 \right|^2 + \lambda_4 \left| H_1 H_2 - v_1 v_2 \right|^2 + \lambda_5 \left( H_1 H_2 - v_1 v_2 + N^2 - v_N^2 \right)^2 + \lambda_6 \left| H_1^+ H_2 \right|^2.$$  

Taking all the $\lambda$’s real and positive guarantees that the absolute minimum of the potential is at $\langle H_1^+ \rangle = v_1$, $\langle H_2^+ \rangle = v_2$, and $\langle N \rangle = v_N$, with zero vacuum expectation values for all the other fields.

There are 6 physical Higgs bosons: one charged Higgs boson $H^\pm$, two neutral “pseudoscalars” $P_1$ and $P_2$, and three neutral “scalars” $S_1$, $S_2$, and $S_3$ (I label the $P$s and $S$s in order of increasing mass). The charged Higgs boson is $H^+ = H^* \sin \beta + H_2^+ \cos \beta$, and its mass is $m_{H^+} = \lambda_4^{1/2} v$, where $\tan \beta = v_2/v_1$ and $v = \sqrt{v_1^2 + v_2^2}$.

The two pseudoscalars are linear combinations $P_k = U_{E_k}^\dagger A + U_{E_k}^\dagger N_I$ of $A = \sqrt{2}(\sin \beta \text{ Im } H_1^0 + \cos \beta \text{ Im } H_2^0)$ and $N_I = \sqrt{2} \text{ Im } N$. The unitary matrix $U^P$ diagonalizes

$$M_P^2 = \begin{pmatrix} (\lambda_4 + \lambda_5) v^2 & 2\lambda_5 v v_N \\ 2\lambda_5 v v_N & 4(\lambda_3 + \lambda_4) v_N^2 \end{pmatrix}. \tag{2}$$

The three scalars are linear combinations $S_j = U_{E_j}^\dagger H_{1R} + U_{E_j}^\dagger H_{2R} + U_{E_j}^\dagger N_R$ of $H_{1R} = \sqrt{2} \text{ Re } H_1^0$, $H_{2R} = \sqrt{2} \text{ Re } H_2^0$, and $N_R = \sqrt{2} \text{ Re } N$. The unitary matrix $U^S$ diagonalizes

$$M_S^2 = \begin{pmatrix} 4\lambda_1 v_1^2 + \lambda_5 v_2^2 & \lambda_4 v_1 v_2 & 2\lambda_5 v_2 v_N \\ \lambda_4 v_1 v_2 & 4\lambda_2 v_2^2 + \lambda_5 v_1^2 & 2\lambda_5 v_1 v_N \\ 2\lambda_5 v_2 v_N & 2\lambda_5 v_1 v_N & 4\lambda_3 v_N^2 \end{pmatrix}, \tag{3}$$

where $\lambda_{ij} = \lambda_i + \lambda_j$. 

The Gamma-Ray Halo from Dark Matter Annihilations

Paolo Gondolo

Max Planck Institut für Physik, Föhringer Ring 6, 80805 Munich, Germany
The Higgs bosons couple to the ordinary leptons and quarks and to the new Majorana fermion \( \chi \) through the Yukawa terms

\[
\mathcal{L}_{\text{Yukawa}} = h_u Q H_1 d_R + h_u Q H_2 u_R + h_l L H_1 e_R + h_\chi \bar{\chi} N.
\]

Here \( Q = (u_L, d_L) \) denotes the SU(2) quark doublets, \( L = (\nu_L, e_L) \) the SU(2) lepton doublets, and \( d_R, u_R, e_R \) the SU(2) singlets. Generation indices are suppressed.

When the Higgs fields get vacuum expectation values, the up–type quarks, the down–type quarks and the charged leptons acquire masses \( m_u = h_u v_2 \), \( m_d = h_d v_1 \) and \( m_l = h_l v_1 \), and the new Majorana fermion acquires mass \( m_\chi = \hbar v_N \). The interaction terms of the Higgs fields with the quarks, the leptons and the \( \chi \) read:

\[
\mathcal{L}_{\text{int}} = \frac{g m_\chi}{2 m_W} \frac{v}{v_N} \left[ \bar{\chi}_j S_j U_{j3}^d + i \bar{\gamma}_5 \chi P_j U_{j1}^d \right] \\
+ \frac{g m_u}{2 m_W} \left[ \bar{u} u S_\beta \frac{U_{33}^u}{\sin \beta} + i \bar{\gamma}_5 u P_j U_{j1}^u \cot \beta \right] \\
+ \frac{g m_d}{2 m_W} \left[ \bar{d} d S_\beta \frac{U_{33}^d}{\cos \beta} + i \bar{\gamma}_5 d P_j U_{j1}^d \tan \beta \right].
\]

Now I find the interesting region in parameter space in which the calculated gamma-ray emission matches the Dixon et al. maps while satisfying present observational and experimental constraints.

The gamma-ray intensity from \( \chi \chi \) annihilations in the galactic halo is given by

\[
\phi_\gamma(b, l, E) = \frac{n_\gamma(E)}{4 \pi m_\chi^2} \int \rho_\chi^2 dl,
\]

where \( \phi_\gamma(b, l, E) \) is in photons/(cm\(^2\) s sr), \( n_\gamma(E) \) is the number of photons per annihilation with energy above \( E \), \( \sigma v \) is the \( \chi \chi \) annihilation cross section times relative velocity at \( v = 0 \), \( \rho_\chi \) is the \( \chi \) mass density in the halo, and the integral is along the line of sight. For a canonical halo, \( \rho(r) = \rho_{\text{loc}}(r_c^2 + R^2)/(r_c^2 + r^2) \), the integral depends only on the angular distance \( \psi \) from the galactic center, and is practically independent of the halo core radius \( r_c \) at \( \psi = 56^\circ \), where it is \( \int \rho_\chi^2 dl = 2 \rho_{\text{loc}} R \). Notice that for this halo model, the intensities at \( \psi = 40^\circ \) and at \( \psi = 60^\circ \) are approximately in the ratio 2:1 as on the Dixon et al. maps.

I consider interesting those parameter values for which the calculated gamma-ray flux at \( \psi = 56^\circ \) is between 7 and 8 times \( 10^{-7} \) photons/cm\(^2\) s sr for a local dark matter density \( \rho_{\text{loc}} \) in the range 0.3–0.5 GeV/cm\(^3\) and a distance from the galactic center \( R = 8 \) kpc. Fig. 1 shows the interesting region in the \( \sigma v - m_\chi \) plane (a point for each choice of parameter values). The figure includes the bounds discussed in the following.
\[ \langle \sigma v \rangle \] is the thermally averaged annihilation cross section at temperature \( x_m \). Since freeze-out occurs below the QCD phase transition, I take \( g_* = 81 \) for the relativistic degrees of freedom at freeze-out. The result of the relic density calculation is shown in Fig. 2. The relic abundance in the interesting region turns out to be in the cosmologically interesting range: \( \Omega_\chi \sim 0.1 \) for a Hubble constant of 60 km/s/Mpc.

In the interesting region, two Higgs bosons, \( S_1 \) and \( P_1 \), are light, with masses between 2 and 16 GeV. They are mostly singlets and their production in colliders is very suppressed. First, I consider the LEP bounds on the search of Higgs bosons in two-doublet models. Since there is an additional Higgs singlet, \( \sin^2(\beta - \alpha) \) in the bound from \( e^+ e^- \rightarrow Z h \) must be replaced with \( |U_{11}^S \cos \beta + U_{12}^S \sin \beta|^2 \), and \( \cos^2(\beta - \alpha) \) in the bound from \( e^+ e^- \rightarrow h A \) must be replaced with \( |U_{12}^P U_{12}^S - U_{11}^P U_{11}^S|^2 \).

In the allowed region, the reinterpreted \( \sin^2(\beta - \alpha) \) and \( \cos^2(\beta - \alpha) \) are smaller than \( 5 \times 10^{-5} \), and are not excluded by accelerator searches. Secondly, I consider Higgs bremsstrahlung from final state leptons and quarks in \( Z \) decays. I find

\[
\frac{\Gamma(Z \rightarrow f \bar{f} X)}{\Gamma(Z \rightarrow f \bar{f})} = \frac{\sqrt{2} G_F}{4 \pi^2} g \left( \frac{m_X}{m_Z} \right) c_f m_f^2 A_{Xf},
\]

where \( A_{P,f} = U_{i1}^P \cot \beta, A_{S,f} = U_{i1}^S / \cos \beta \) for up-type quarks, \( A_{P,f} = U_{i1}^P \tan \beta, A_{S,f} = U_{i2}^S / \sin \beta \) for down-type quarks and leptons, \( c_f = 3 \) for quarks and \( c_f = 1 \) for leptons. The function \( g(y) \) comes from the phase-space integration, and is \( g(y) \approx 1 \) at \( m_X = 12 \) GeV. The most stringent constraint from the LEP results on two leptons + two jets production is \( \Gamma(Z \rightarrow f \bar{f} X)/\Gamma(Z \rightarrow f \bar{f}) < 1.5 \times 10^{-4} \) at \( m_X = 12 \) GeV. The highest values I find in the interesting region of my model are of order \( 10^{-6} \), and so this constraint is easily satisfied.

In addition to accelerator bounds, the \( \chi \) particle must satisfy present bounds from direct and indirect dark matter searches. The cross section for elastic \( \chi \)–proton scattering, which is spin-independent, is

\[
\sigma_{\chi p} = \frac{G_F^2}{\pi} \frac{2m_p^4 m_X^4}{(m_p + m_X)^2} \frac{v^2}{v_N} \left[ \sum_{j=1}^{3} U_{j\beta}^S \left( k_d U_{j1}^S + k_u U_{j2}^S \right) \right]^2,
\]

where \( k_d = \langle m_d \bar{d} d + m_s \bar{s} s + m_b \bar{b} b \rangle = 0.21 \) and \( k_u = \langle m_u \bar{u} u + m_c \bar{c} c + m_t \bar{t} t \rangle = 0.15 \). Fig. 3 shows a comparison of this cross section with the presently most stringent upper bound on few GeV WIMPs. The bound touches the interesting region, but to explore it all major improvements in sensitivity are needed, especially at low thresholds.

The \( \chi \) fermions can also accumulate in the Sun and in the Earth cores, annihilate therein and produce GeV neutrinos. Accumulation in the Earth is not efficient because the \( \chi \) mass is below the evaporation mass from the Earth (~ 12 GeV), and no neutrino signal is expected from there. The evaporation mass in the Sun (~3 GeV) is in the middle of the interesting region. Following Ref. [10], I have calculated the neutrino flux from the Sun including evaporation, annihilation and capture, and then the rate of contained events and the flux of through-going muons in neutrino telescopes. I have imposed the experimental bounds in Ref. [10]. Fig. 4 shows that, although the present limits on through-going muons constrain the allowed region, it will be difficult to probe models with \( m_\chi \) below the evaporation mass of ~ 3 GeV because of the exponential suppression of the signal.
The flux of through-going muons from the Sun induced by neutrinos from $\chi$ annihilations versus the $\chi$ mass. The solid lines are the Baksan and MACRO limits [10]; the dots show the interesting region.

The clearest test of WIMP annihilations in the halo is the shape of the gamma-ray spectrum. It must show a sharp cutoff and a gamma-ray line at the WIMP mass. The continuum spectrum is determined from jet physics. The gamma-ray line intensity is proportional to the annihilation cross section into two photons, which in the specific model presented here results in the range $10^{-29}$–$10^{-30}$ cm$^3$/s (using formulas in Ref. [11]). The poor energy resolution of present gamma-ray detectors unfortunately smears the line out: even a tantalizing energy resolution of 0.1% merely gives $10^{-12}$ photons/cm$^2$/s/sr/MeV in this model. Fig. 5 illustrates the gamma-ray spectrum expected from $\chi\chi$ annihilations for $\chi$ particles in the interesting region. For comparison, the figure indicates the measured extragalactic flux [12]. Since the antiproton constraint limits the $\chi$ mass to less than 4.3 GeV, a clear detection of halo gamma-rays more energetic than this would be an indication against the present WIMP model.

In conclusion, it is possible to explain the Dixon et al. gamma-ray halo as due to WIMP annihilations in the galactic halo. As illustrated in an explicit model, not only the intensity and spatial pattern of the halo emission can be matched but also the relic density of the candidate WIMP can be in the cosmologically interesting domain. The model is quite predictive and can be tested with a variety of techniques, above all by accurately measuring the energy spectrum of the halo gamma-ray emission.

I thank D. D. Dixon for discussions.

[1] D. D. Dixon et al., in Sources and Detection of Dark Matter in the Universe, Marina del Rey, California, February 1998; preprint astro-ph/9803237 (March 1998).
[2] P. Gondolo, in New Trends in Neutrino Physics, Ringberg Castle, Tegernsee, Germany, May 1998.
[3] W. R. Webber, M. A. Lee, and M. Gupta, Ap. J. 390, 96 (1992); P. Chardonnet, G. Mignola, P. Salati, and R. Taillet, Phys. Lett. B384, 161 (1996); A. Bottino, F. Donato, N. Fornengo, and P. Salati, astro-ph/9804137 (April 1998).
[4] A. Moiseev et al. (BESS Collab.), Ap. J. 474, 479 (1997).
[5] E. W. Kolb and M. S. Turner, The Early Universe (Addison-Wesley, Redwood City, 1990); P. Gondolo and G. Gelmini, Nucl. Phys. B360, 145 (1991).
[6] D. Decamp et al., Phys. Rep. 216, 253 (1992).
[7] R. Bernabei et al., Phys. Lett. B 389, 757 (1996); University of Rome preprint ROM2F/98/08 (February 1998).
[8] M. Sisti et al. (CRESST Collab.), in Low Temperature Detectors 7, Munich, Germany, July 1997.
[9] K. Griest and D. Seckel, Nucl. Phys. B 283, 681 (1987); A. Gould, Ap. J. 321, 571 (1987); G. Gelmini, P. Gondolo, and E. Roulet, Nucl. Phys. B 351, 623 (1991); M. Kamionkowski and G. Jungman, Phys. Rev. D 51, 328 (1995).
[10] N. Sato et al. (Kamiokande Collab.), Phys. Rev. D 44, 2220 (1991); O. Suvorova (Baksan Collab.), in Non-Accelerator New Physics 97, Dubna, Russia, July 1997; T. Montaruli (MACRO Collab.), in Dark 98, Heidelberg, Germany, July 1998.
[11] Z. Bern, P. Gondolo, and M. Perelstein, Phys. Lett. B411, 86 (1997).
[12] P. Sreekumar et al., Ap. J. 494, 523 (1998).