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PROBING THE STRUCTURE OF THE GALACTIC HALO WITH GAMMA RAYS PRODUCED BY WIMP ANNIHILATIONS

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ABSTRACT

It has recently been pointed out that the annihilations of a class of possible dark matter halo constituents (including photinos, higgsinos, and heavy neutrinos or sneutrinos) within the halo of our galaxy produce a series of narrow gamma-ray lines. If these lines are detected, then the directional dependence of the intensity of the lines provides a very powerful probe of the halo mass distribution, and the local density, core radius, and ellipticity of the halo could be readily determined. We briefly comment on the possibility of detecting WIMP annihilations in the galactic spheroid.

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I. Introduction

There is now overwhelming evidence that the primary component of the mass density of the halos of spiral galaxies and of the Universe itself is 'dark' (for a recent review of this subject, see ref. 1). Clearly, the nature and total amount of dark matter in the Universe is one of the most pressing questions facing cosmologists today. An intriguing and attractive possibility is that the dark matter is relic, Weakly-Interacting Massive Particles (or WIMPs) left over from the very hot, early moments of the Universe. Particle physics has provided a long list of candidate WIMPs -- axions, light neutrinos, photinos, higgsinos, sneutrinos, heavy neutrinos, and many, many more (for further discussion, see ref. 1).

Until very recently it was believed that in spite of their great cosmic abundance, these relic WIMPs would be undetectable because of the feebleness of their interactions. As it has turned out, this early pessimism was somewhat premature. A variety of clever techniques have been proposed for the detection of WIMPs in the halo of our galaxy. For example, halo axions will convert to photons in a strong, inhomogeneous magnetic field[2]; halo photinos will annihilate into protons and antiprotons some fraction of the time, giving rise to antiprotons in the cosmic rays[3]; a variety of halo WIMPs will deposit small, but potentially detectable amounts of energy in supercooled, bolometric detectors[4] (such detectors are still to be built however); halo WIMPs captured by the sun or earth will annihilate inside these bodies, giving rise to a flux of several hundred MeV neutrinos which may be detectable in large underground detectors.[5]

In a very recent letter Srednicki etal.[6] have pointed out that a class of WIMP candidates (including photinos, higgsinos, heavy Majorana neutrinos, and sneutrinos) will annihilate into a quarkonium state ($Q\bar{Q}$; $Q\bar{Q} = \psi/J, \psi', \ldots; \Upsilon, \Upsilon', \ldots$) and a monoenergetic photon some fraction of the time (few $\times 10^{-3}$)

$$\text{WIMP} + \text{anti-WIMP} \rightarrow (Q\bar{Q}) + \gamma \ .$$

Because of the narrowness of the quarkonium states and the relatively low velocity dispersion of the halo ($\simeq 10^{-3}$ c), these gamma ray lines (one for each $J^P = 1^-$ quarkonium state whose production is kinematically allowed) should be very narrow, $\Delta E_\gamma/E_\gamma \simeq 10^{-3}$. Srednicki etal.[6] argue that these very characteristic lines could be detected by the Gamma Ray Observatory (GRO) which is to be put into orbit by NASA within the next few years. They also point out that if such lines are detected, the energies of the lines would allow a unique determination of the mass of the halo WIMPs. In this brief report we point out that, in addition, the directional dependence of the intensity of the lines would provide a powerful probe of the halo mass density, allowing a straightforward determination of the local density, core radius, and ellipticity of the halo of our galaxy.

II. Probing the Halo Through WIMP Annihilations

The gamma ray flux from a given direction due to WIMP annihilations into quarkonium + photon is

$$F(\theta,\phi) = (\sigma v/4\pi m^2) \int_0^\infty \rho^2(r)dr(\theta,\phi) \ , \tag{1}$$

where $\rho(r)$ is the halo density in WIMPs, (σv) is the cross section for annihilation into $(Q\bar{Q}) + \gamma$, m is the WIMP mass, and the integration procedes along the direction of observation, denoted by θ and ϕ. [Our coordinate system is shown in Fig. 1; θ is the angle out of the galactic plane, or galactic latitude, and ϕ is the angle in the galactic plane away from the direction of the galactic center, or galactic longitude; ψ is the angle between the galactic center and direction of observation and $\cos\psi = \cos\theta\cos\phi$.] Since the annihilations which produce quarkonium proceed via the s-wave, (σv) is velocity independent. The key feature of Eqn. (1) is that the integrated flux along a given direction depends upon the line integral of the halo density squared.

The Galaxy is generally believed to consist of three components: the luminous central spheroid, the disk, and the extended dark halo. The most likely place to find WIMPs is in the dark halo which accounts for most of the mass in the galaxy. The halo density is expected to be that of an isothermal sphere ($\rho \propto 1/(a^2+r_c^2)$; a = the core radius). As a definite, and slightly more general model, we write the halo density in WIMPs as

$$\rho(\vec{r}_c) = \rho_o(a^2+R^2)[a^2 + x_c^2/\alpha^2 + y_c^2 + z_c^2/\gamma^2]^{-1} \ , \tag{2}$$

where ρ_o is the local halo density, R is our galactocentric distance ($\simeq$ 8 kpc $\simeq 2.5 \times 10^{22}$cm), and (x_c, y_c, z_c) are coordinates relative to the center of the galaxy (see Fig. 1). This model describes a halo whose

surfaces of constant density are ellipsoids, whose core radius is a, and whose density decreases as 1/distance^2 at large distances. The major axes of the ellipsoids of constant density are: $(\alpha,1,\gamma)$, where the z-axis is out of the galactic plane and the vector from the galactic center to our position lies along the y-axis. Modeling of the galactic halo indicates that R/a is of order unity and that ρ_o, the local halo density, is about 5×10^{-25}g cm^{-3} (refs. 7,8). Little is known about the ellipticity of the halo. The total mass of such a halo diverges, and so any such model must have a cutoff ellipsoid, say $\rho = 0$ on the ellipsoid where $(N^2 - 1)a^2 = x_c^2/\alpha^2 + y_c^2 + z_c^2/\gamma^2$. Because $F \propto \int \rho^2 dr$, we find that the integrated flux in any direction is insensitive to this cutoff so long as $N \gg 1$.

Using this model for the halo density and defining the following quantities

$$\xi^2 = \sin^2\theta/\gamma^2 + \cos^2\theta(\cos^2\phi + \sin^2\phi/\alpha^2) \ , \tag{3a}$$

$$b^2 = a^2 + R^2(1 - \cos^2\psi/\xi^2) \ , \tag{3b}$$

it is straightforward to compute the integrated gamma ray flux from a given direction

$$F(\theta,\phi) = (\sigma v/4\pi m^2)\rho_o^2 R\left(\frac{a^2+R^2}{b^2}\right)^2 \frac{b}{R\xi}\, I(\theta,\phi), \tag{4a}$$

$$I(\theta,\phi) = \int_{-R\cos\psi/\xi b}^{(N^2a^2/b^2-1)^{1/2}} du/(1+u^2)^2 \ , \tag{4b}$$

$$\int^u du'/(1+u'^2)^2 = \frac{1}{2}\frac{u}{1+u^2} + \frac{1}{2}\tan^{-1}u. \tag{4c}$$

For reference, $\rho_o^2 R \simeq 6.2 \times 10^{-27} g^2\ cm^{-5}$.

Note that the gamma ray flux depends upon $(\sigma v/m^2)\rho_o^2$, θ, ϕ, R/a, and the ellipticity of the halo (specified by α and γ). The insensitivity of the geometrical integral $I(\theta,\phi)$ to the halo cutoff is apparent as

$$\int^u du'/(1+u'^2)^2 \xrightarrow[u>>1]{} \pi/4 - 1/3\ u^{-3} + 2/5\ u^{-5} - +\ldots$$

In all of our calculations we will assume that $N >> 1$.

Some general comments about $I(\theta,\phi)$ are in order. For reference, Srednicki <u>etal.</u>[6] used the value $(b/R\xi)\ ((a^2+R^2)/b^2)^2 I = 5$ for their estimates of the gamma ray flux. (1) $I(\theta,\phi)$ achieves its maximum value in the direction $\theta = \phi = 0$ as one would expect since the halo density is peaked about the center of the galaxy. $I(0,0)$ is independent of α and γ. For $R/a = 1$, $I(0,0) = 5.712$; in the limits $R/a \to 0$ and ∞, $I(0,0) \to a/R$ and $(\pi/2)\ (R/a)^3$ respectively. (2) $I(\theta,\phi)$ is most sensitive to R/a in the $\phi = 0°$-plane. $I(\theta,0°)$ is shown in Fig. 2 for $\alpha = \gamma = 1$ and $R/a = 2$, 1, and 1/3. The galactic center (θ=0°)/anti-center (θ=180°) asymmetry becomes more apparent for small core radius ($R/a >> 1$)

$$I(0°,0°)/I(180°,0°) \to \begin{cases} 1 & R/a << 1 \\ \frac{3\pi}{2}(R/a)^3 & R/a >> 1 \end{cases}$$

(3) The effect of halo ellipticity is most pronounced in the $\phi = 90°$-plane. For $\alpha = \gamma = 1$, $I(\theta,90°)$ is independent of θ. For $\alpha = 1$, $I(90°,90°) = \gamma I(0°,90°)$; see Fig. 3. (4) From 4 measurements one could in principle determine ρ_o, R/a, α, γ. To illustrate this consider the four directions: a -- $\theta=90°$; b -- $\theta=0°$, $\phi=90°$; c -- $\theta=\phi=0°$; d -- $\theta=180°$, $\phi=0°$. The fluxes in these directions are given by

$$F_a = (\sigma v/4\pi m^2)\rho_o^2 R\gamma(1+a^2/R^2)^{1/2}\ \pi/4 ,$$

$$F_b = (\sigma v/4\pi m^2)\rho_o^2 R\alpha(1+a^2/R^2)^{1/2}\ \pi/4 ,$$

$$F_c = (\sigma v/4\pi m^2)\rho_o^2 R(1+R^2/a^2)^2(\pi/4 + \int_o^{R/a} du/(1+u^2)^2) ,$$

$$F_d = (\sigma v/4\pi m^2)\rho_o^2 R(1+R^2/a^2)^2(\pi/4 - \int_o^{R/a} du/(1+u^2)^2) .$$

Using the quantity $(F_c - F_d)/(F_c + F_d)$ one could determine R/a. From this, one could determine ρ_o (assuming that one could calculate or otherwise deduce $\sigma v/m^2$). The fluxes F_a and F_b could then be used to determine α and γ. Additional observations would serve to test the original halo model.

Finally, we briefly mention a very intriguing, but probably less likely possibility recently suggested by Silk,[9] the possibility that some fraction of the central spheroid component is WIMPs. As we will see the flux from such a component could be enormous and would have a very well-defined signature. As a model of the spheroid we use

$$\rho_{sp} = c/(a_s^2 + r_c^2)^{3/2} \ , \tag{5}$$

where the core radius of the spheroid $a_s \simeq O(100\ \mathrm{pc})$, $c = M_{sp}/(4\pi\ c')$, M_{sp} is the total mass of the spheroid $\simeq 3 \times 10^9\ M_\odot$, and c' is a number of order unity. [Since the total mass of the spheroid diverges logarithmically for a so-called Hubble law profile, $\rho_{sp} \propto r_c^{-3}$, c' depends logarithmically on the cutoff chosen.] For further discussion of the properties of the galactic spheroid see ref. 10.

Using this density profile and assuming that a fraction f of the spheroid density is due to WIMPs (with the same spatial distribution) it is straightforward to compute the γ-ray line flux:

$$F \simeq f^2(\sigma v/4\pi m^2)(M_{sp}/4\pi c')^2\ b_s^{-5}\int_{-R\cos\psi/b_s}^{\infty} du/(1+u^2)^3 \ , \tag{6}$$

$$\int^{u} du'/(1+u'^2)^3 = (u/4)/(1+u^2)^2 + (3u/8)/(1+u^2) + (3/8)\tan^{-1}u \ ,$$

where as before $b_s^2 = a_s^2 + R^2\ (1-\cos^2\psi)$. Because of the b_s^{-5} factor and the fact that $a_s \ll R$, F is very sharply peaked in the direction of the galactic center ($\theta = \phi = \psi = 0$). Physically this is because $F \propto \rho^2 \propto r_c^{-6}$, which is very strongly peaked at $r_c = 0$. For directions near the galactic center we have: $-R\cos\psi/b_s \ll -1$ and $\int du/(1+u^2)^3 \rightarrow 3\pi/8$. The flux in this direction is then

$$F \simeq 10^{-20}\ g^2 cm^{-5}\ f^2(\sigma v/4\pi m^2)(M_{sp}/3\times10^9 M_\odot)^2 \\ (100\ \mathrm{pc}/a_s)^5 \quad (a_s/b_s)^5 \ , \tag{7}$$

which for $f \simeq 1$ is about a factor of 10^6 greater than the typical flux from halo WIMP annihilations, cf., Eqn. (4). Because of the $(a_s/b_s)^5$ factor in Eqn. (7) the flux is strongly direction-dependent, falling off by a factor of 2 for an angle $\psi \simeq 0.56\ a_s/R \simeq 5.6 \times 10^{-3}(a_s/100\text{pc}) \simeq 0.3°(a_s/100\text{pc})$ from the galactic center. The fall off in intensity with ψ provides a direct measure of the core radius of the spheroid.

III. Concluding Remarks

Other than the fact that it exists, we know precious little about the major mass component of our galaxy -- the halo. If the narrow gamma ray lines associated with WIMP annihilations in the galactic halo predicted by Srednicki etal.[6] are detected by GRO or some other gamma ray telescope, we will have a valuable new probe of the halo of our galaxy. Measurements of the directional dependence of the line flux would, as we have discussed, serve well to determine the core radius, local density, and ellipticity of the halo. Owing to the $\rho^2(r)$ dependence on the halo density, little of the gamma ray flux comes from far beyond the core of the halo, so that the cutoff radius of the halo is not likely to be measured by this method. If one had good reason to believe that the constituents of the dark matter were particles whose annihilations produced such narrow gamma ray lines and if one could predict the energies of the lines (e.g., if the photino or sneutrinos were discovered at the Tevatron $p\bar{p}$ collider and its properties were determined), one might consider proposing a dedicated, hi-resolution gamma ray telescope to detect these gamma ray lines, with the hope of directly verifying the existence of WIMPs in the galactic halo and

probing the structure of the halo. It could even be that some fraction of the galactic spheroid is WIMPs, which would result in a very strong γ-ray line flux from the galactic center.

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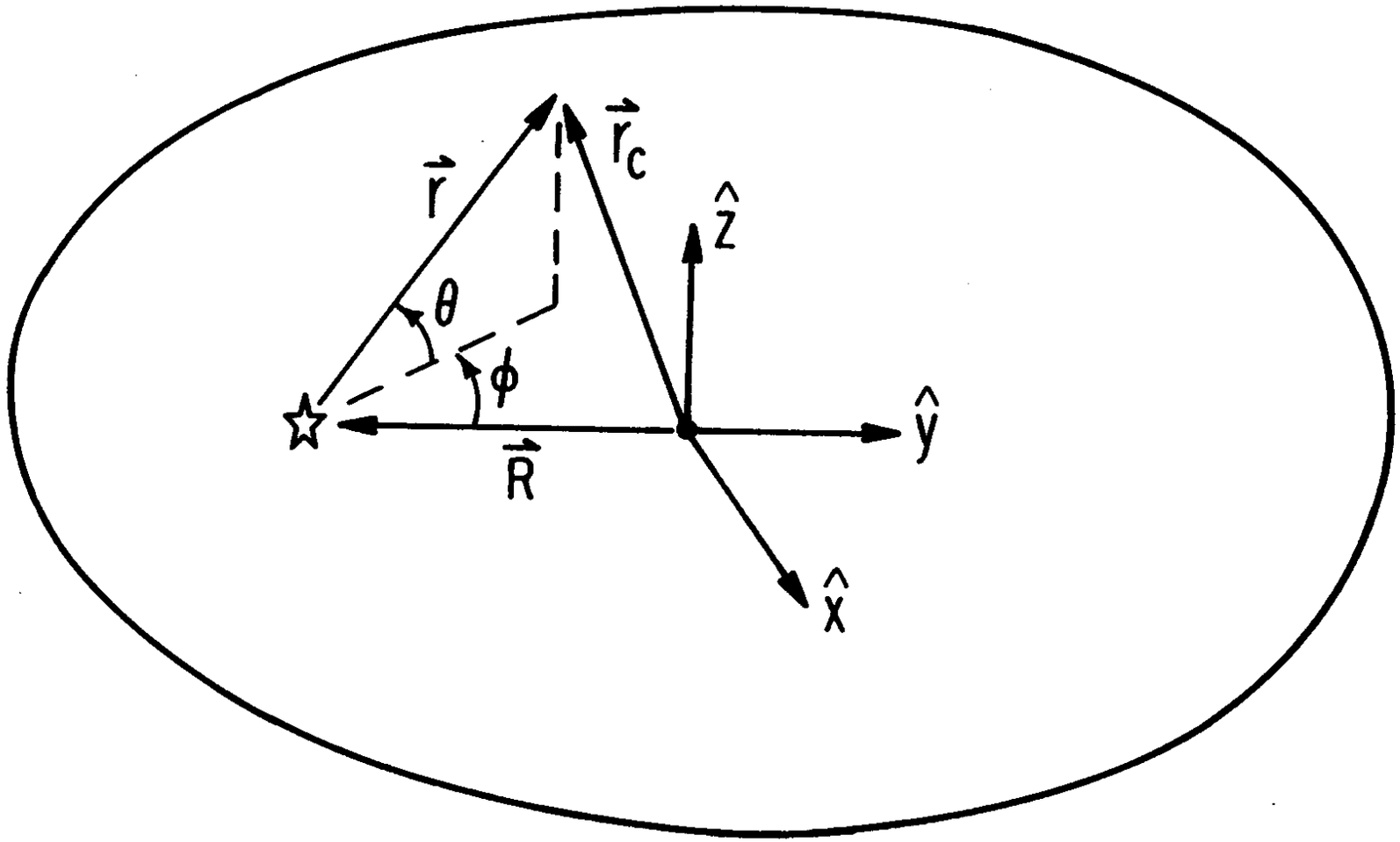
FIGURE CAPTIONS

Fig. 1 - The coordinate system used throughout. The direction of observation is specified by θ and ϕ. $\vec{R}$ specifies our position in the galaxy and $\vec{r}(\vec{r}_c)$ is the position of an arbitrary point in the halo relative to the solar system (galactic center). The angle between the direction of observation and the galactic center ψ, is given by: $\cos\psi = \cos\theta\cos\phi$.

Fig. 2 - The geometric integral $I(\theta,\phi)$ for $\phi=0$, $\alpha=\gamma=1$ as a function of θ for $R/a = 2$, 1, and 1/3. For large R/a, the galactic center-anticenter asymmetry becomes very pronounced.

Fig. 3 - The geometric integral $I(\theta,\phi)$ for $\phi=90°$, $\alpha=1$ as a function of θ for $\gamma = 3$, 1, 1/3. The θ-dependence of $I(\theta,\phi)$ in the $\phi=90°$-plane indicates ellipticity of the halo.



GALACTIC DISK

FIG. 1

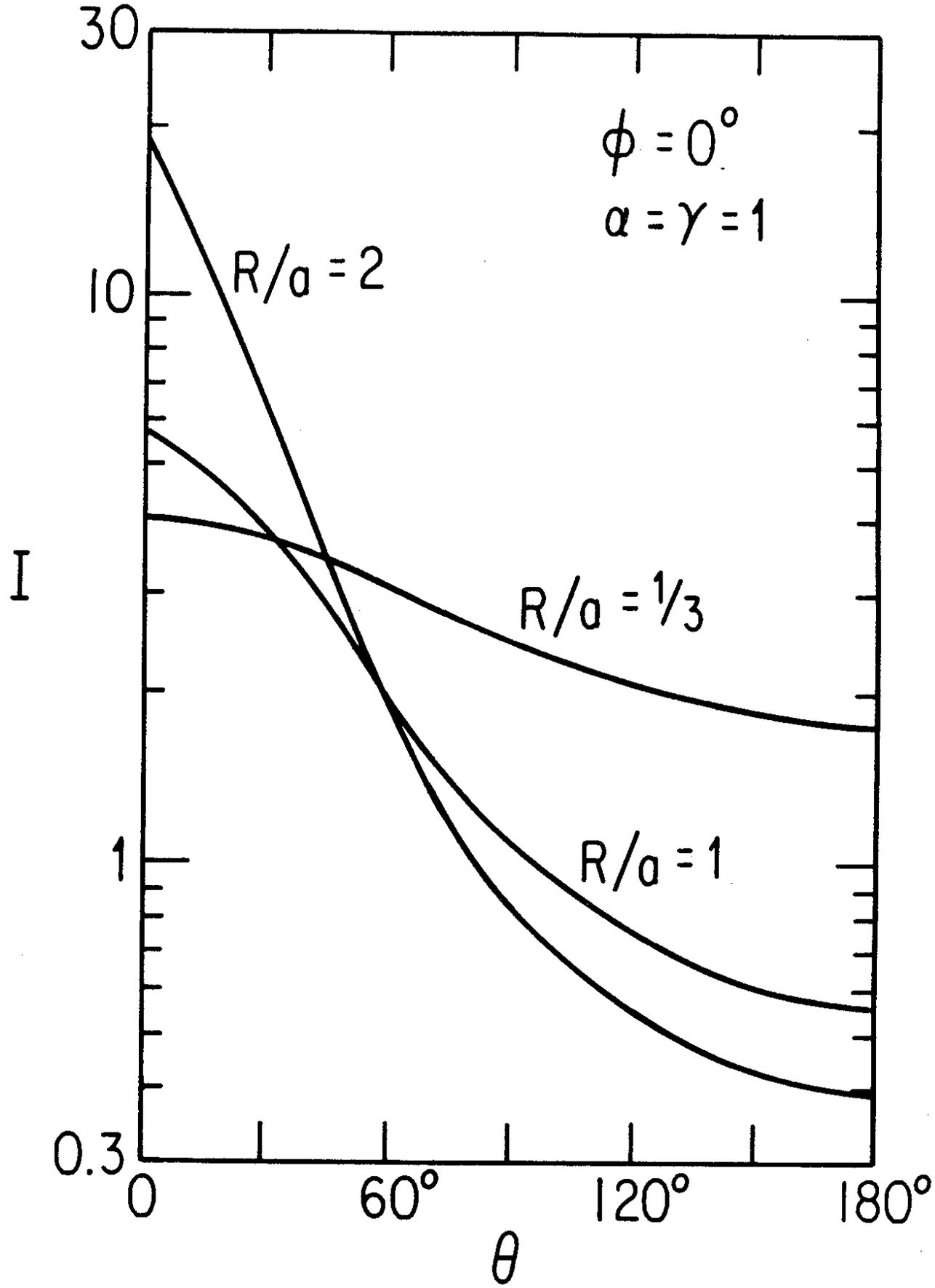


FIG. 2

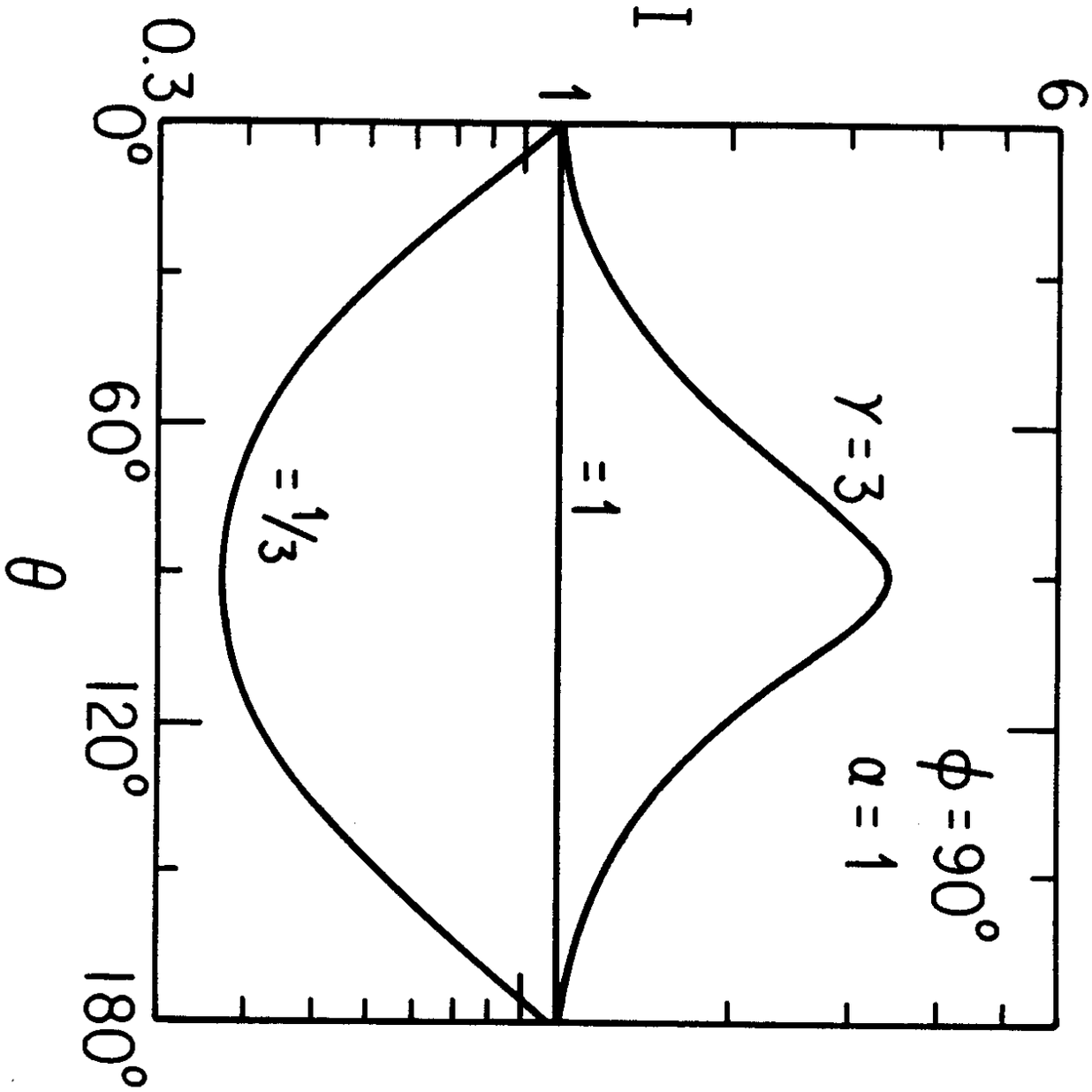


FIG 3