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Distinguishing between Stars and Galaxies Composed of Matter and Antimatter Using Photon Helicity Detection

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The positrons produced in fusion processes in matter stars will have predominantly a "right" helicity due to the nonconversation of parity in weak interactions. This helicity is transferred to bremsstahlung and forward in-flight annilation radiation, which will be right-circularly polarized. In antimatter stars, *CP* symmetry will make the equivalent radiation left-circularly polarized. The helicity of such radiation can be used to distinguish between astronomical objects composed of matter and antimatter.

The tantalizing possibility that macroscopic quantities of antimatter may exist in our universe has been the subject of calculation and speculation for more than two decades.[1] Baryon-symmetric cosmologies have been proposed which would required equal amounts of matter and antimatter to be present in the universe.[2] It has also been proposed that a black hole composed of normal matter may "evaporate" equal amounts of matter and antimatter,[3] tending to symmetrize the matter-antimatter balance of the universe if it were not *a priori* symmetric.

In a recent review article, Steigman[4] pointed out that all methods of locating antimatter in the universe which have so far been suggested (except for antineutrino detection) require the introduction of normal matter into a region of space which contains antimatter, or vice versa, so that matter-antimatter annihilation takes place and can be observed. In the present work we suggest an alternative method which uses the helicity of secondary electromagnetic radiation produced by stellar fusion processes to distinguish between stars composed of matter and antimatter. This method, though very difficult, does not require matter-antimatter annihilation or antineutrino detection.

It would seem at first sight that the symmetry of the physical processes in stars composed of matter and of antimatter would make them observationally identical so that no way could be found of distinguishing between them. However, there is one exception to this general symmetry which arises from the nonconservation of parity in the weak interactions and from *CPT* symmetry.[5] The thermonuclear processes which occur in stars, whether involving the hydrogen cycle, the carbon cycle, or nucleosynthesis of heavier elements, systematically convert protons into neutrons. This conversion takes place through the weak-interaction processes of β^+ decay and electron capture. When positrons (β^+) are emitted they will be preferentially in a "right"-helicity state of strength v/c as a consequence of the nonconservation of parity and the maximal parity nonconservation in β decay. Thus the positron spins will be aligned along their lines of flight.[5] The emission of these positrons may be accompanied by the emission of *inner* bramsstrahlung,[5] and when they are slowed in matter they are likely to produce *external* breamsstrahlung. The helicity of the positron will be transferred to both of these types of bremsstrahlung, making them right-circularly polarized.[6,7] In other words, the bremsstrahlung helicity, like that of the positron, will be such that the spin is aligned along the photon's line of flight.

The polarized positrons may also undergo annihilation in flight in which the energetic positron strikes an electron at rest, producing two photons, one along the line of flight of the positron and one in the opposite direction. The forward-going annihilation photon, which has most of the energy, will preferentially have the same helicity as the positron.[8]

A fourth source of polarized secondary radiation is the internal bremsstrahlung which accompanies the weak-interaction process of electron capture. Here the sudden change in the charge of the nucleus by one unit produces a "shock" which induces inner bremsstrahlung with a probability on the order of the fine-structure constant. This electromagnetic radiation has preferential helicity which closely corresponds to the helicity of inner bremsstrahlung induced by β^+ emission.[9] Thus, three bremsstrahlung processes and annihilation in flight all produce energetic radiation which is right-circularly polarized.

For antimatter stars, exactly the same processes will take place except that the burning processes will convert *anti*protons into *anti*neutrons, producing antipositrons, i.e., electrons. As a consequence of *CPT* symmetry (actually *CP* symmetry since time reversal is not involved), these electrons will have their spins aligned *antiparallel* to their lines of flight and produce bremsstrahlung and forward in-flight annihilation radiation which are *left*-circularly polarized.[5] Thus the secondary energetic photons produced by thermonuclear processes in matter and antimatter stars will tend to be polarized with opposite helicitites. Hence, an asymmetry exists between matter and antimatter which, in principle, allows one to distinguish between the two without the necessity of annihilation between them.

The existence of a possible method of distinguishing between matter and antimatter stars and galaxies brings into sharp focus the question of whether this radiation is actually observable. The thermonuclear processes which produce the radiation of interest normally occur deep in the stellar interior, and the radiation would have to traverse an enormous number of mean free paths of stellar matter before reaching the surface and escaping. It would thus appear that there is little possibility of directly observing this radiation if it originates within a normal star.

On the other hand, a supernova, even one located in another galaxy, offers the possibility of direct observation of the matter/antimatter helicity. It is believed that this type of stellar explosion occurs when the fusion processes in a massive star have terminated with the production of a large quantity of ^{56}Ni at the peak of the binding-energy curve, so that the fusion fuel of the star is exhausted. The ^{56}Ni decays by electron capture to ^{56}Co, which decays by electron capture and positron decay (18% branch and 1.46 MeV end-point energy) to ^{56}Fe.[10] A large fraction of the energy released after a supernova explosion is ascribed to this decay sequence, and under the assumption that the stellar envelope blows off, most of the expected energy release of energetic photons occurs at the *surface*. Moreover, the positrons are emitted in a medium which is predominantly iron (rather than hydrogen), increasing the probability of bremsstrahlung by a factor of $(Z_{\text{Fe}}/Z_{\text{H}})^2$ or 676. Therefore, the probability of directly observing the polarized secondary radiation from this decay sequence should be greatly enhanced.

Let us estimate the minimum flux of energetic photons from a matter/antimatter object. Following Clayton,[10] we consider the case of a supernova 1.0 Mpc away in which 0.14 solar masses of material is released in the form of ^{56}Ni, and in this minimum estimate, we only consider the photons produced by the inner-bremsstrahlung process. The later is likely to be only a small fraction of the total photons of interest, but since it occurs as part of the weak-interaction decay it can be estimated without making assumptions about the nature of the medium in which the positrons are stopping. We reduce the estimate of Clayton[10] by the factor reflecting the probability of inner-bremsstrahlung production and find that the peak flux occurs about 1 month after the onset of the supernova and has a value of about 2×10^{-2} photons/m^2 sec with a mean photon energy of about 0.2 MeV and a mean helicity of about 25%. If a polarimeter 1 m in diameter, mounted in space, accumulates counts for a period of about 1 yr starting within 2 weeks after the supernova is observed to initiate, the polarimeter would process about 3×10^5 events, which should permit a determination of the *sign* of the helicity. However, as previously mentioned, the photon flux from external bremsstrahlung may be 10^2–

10^3 times larger than produced by inner bremsstrahlung, because of the presence of the iron stopping medium. As a benchmark for the difficulty of these measurements in the present state of γ-ray astronomy, it should be noted that even the direct γ-ray transitions from the ^{56}Ni-decay sequence in supernovae have not yet been experimentally observed.[10]

The study of continuum x-rays and γ rays in search of the predicted matter/antimatter helicity will be very difficult, but it has the distinct advantage that there are few strong competing processes which can produce photons of a preferential helicity in this energy region. One alternative process, however, is synchrotron radiation.[11] In magnetic stars such radiation might compete in intensity with bremsstrahlung, particularly at the lower energies, i.e., in the x-ray region and, moreover, this process has been shown to have a nonzero helicity under some circumstances.[11]

Finally, there is the possibility that a small remnant of the matter/antimatter helicity, arising from the effects described above, might remain in visible starlight because of the infrared catastrophe in the bremsstrahlung cross section at low photon energies. McVoy has shown that for low-energy external bremsstrahlung the transferred helicity decreases linearly with decreasing photon energy.[7] Moreover, a given positron is not limited to a single bremsstrahlung event, and may produce a large number of low-energy photons before it is stopped.

It seems likely that in normal stars any residual matter/antimatter helicity in visible starlight will be very small. The case may be somewhat more favorable for light from supernovae because the escape time for visible radiation will be much shorter and the number of scatterings before escape will be much smaller.

Any identification in visible light of the matter/antimatter helicity should be facilitated by its distinctive characteristics: (1) It has the same sign of circular polarization at all wavelengths; (2) the strength of the circular polarization should decrease slowly with increasing wavelength; and (3) the circular polarization should be unrelated to any linear polarization which may present in the same light. Identification of this helicity, however, is made more difficult by a number of other mechanisms which can produce circular polarization in visible light from stars, particularly the Zeeman effect for continuum radiation,[12,13] circular polarization in sunspots,[14] and linear and circular polarization arising from interstellar grains.[15]

A quantitative estimate of the size of the matter/antimatter helicity in visible light is beyond the scope of the present Letter. It will require detailed stellar transport calculations with particular attention to polarization-transfer processes. A formalism suitable for such calculations has been developed by Lipps and Tolhoek,[16] but to our knowledge this formalism has never been applied to astrophysical phenomena.

Let us finally turn to a brief discussion of the experimental techniques available for the measurement of the circular polarization of x rays and γ rays. Recently, a number of x-ray polarimeters for astronomical use have been designed and built.[17] Unfortunately, all of these instruments are designed to measure *linear* polarization and are completely insensitive to the circular polarization of the radiation detected. Therefore, new astronomical x-ray and/or γ-ray polarimeters will have to be designed for the measurements envisioned here.

The only currently available technique for determining the circular polarization of photons in the x-ray and γ-ray region uses the differential Compton scattering of polarized photons from polarized electrons. There is a sizable component of the Compton cross section which changes sign, depending on the relative helicity of the colliding photon and electron. The polarized electrons employed are the valence electrons of a magnetically saturated ferromagnetic material, usually iron.[18] In magnetized iron, unfortunately, only 2 out of 28 orbital electrons are spin aligned and will contribute to the polarization-dependent cross section. Thus, even for 100%-polarized radiation the detection asymmetries would amount to only a few-percent change in the counting rate when the magnetizing field reverses the spins of the valence electrons.

Recently, the prospect of more efficient analyzers of circularly polarized x-rays and γ rays has been raised by theoretical predictions that stable systems of spin-aligned hydrogen (H↑), and deuterium (D↑), and lithium (Li↑) may be feasible at temperatures (0.1–1.0°K) and magnetic fields (~ 50 kG) which are within the reach of present technology.[19] For such analyzers, either all of the electrons (H↑ and D↑) or one out of three electrons (Li↑) will contribute to the polarization-dependent Compton cross section, which would vastly improve the analyzing power.

The polarization-dependent part of the Compton total cross section changes sign at 630 keV. This means that transmission-type polarimeters will only be useful well above (or below) this energy. Scattering-type polarimeters, however, can be used at all energies.[18] They have characteristically poorer energy resolution, but offer the additional advantage that the scattering analyzer can be made much larger than the photon detector itself, so that polarimeters with very large apertures and good background rejection can be contemplated. Clearly then, the polarimeter design is a very challenging problem and the designer will have to deal effectively with the problems of small fluxes, small asymmetry effects, and difficult technologies, particularly since such a polarimeter will have to be located in space while collecting data for the duration of the energetic-photon emission of a supernova, i.e., several months to several years.

In summary, we have proposed that the circular polarization of energetic photons, and possibly also of visible light, may permit stars and galaxies composed of matter and antimatter to be distinguished. The experiments are very difficult but perhaps possible, particularly for supernovae.

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