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ON THE DETECTION OF POSITRONS VIA THE OPTICAL LINES OF POSITRONIUM[1]

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ABSTRACT

It is thought that positrons are copiously produced in active galactic nuclei, the magnetospheres of pulsars, and other high-energy astrophysical systems. However, the most obvious signature of a positron, the 511 keV annihilation line, has been confirmed for only one nonsolar source, the galactic center. In the search for new positron sources, it may prove fruitful to make use of a less well-known signature of a positron, namely, the optical lines emitted when a positron and an electron combine to form positronium. Positronium, an analog of the hydrogen atom, has a recombination-line spectrum with wavelengths which are twice the wavelengths of the corresponding hydrogen lines. On the average, for a wide range of physical conditions, the emission of each 511 keV annihilation-line photon will be preceded by the emission of about one positronium Lyman-α λ2430 photon For both NGC 4151 and the Crab pulsar, the equivalent width of the positronium Lyman-α line is estimated to be approximately 100 mÅ. With Space Telescope, it may be possible to detect (5 σ) such a line from NGC 4151 in about 10^3 s and from the Crab pulsar in about 10^5 s.

Subject headings: elementary particles—galaxies: nuclei — gamma rays: general — line indentifications

I. INTRODUCTION

The most obvious signature of a positron is the 511 keV annihilation line. The line was observed in the laboratory shortly after Anderson's discovery of the positron (Thibaud 1933*a*, *b*, *c*; Curie and Joliot 1933). Recently the annihilation line has been seen from two celestial objects, the Sun (e.g., Share *et al.* 1983) and the galactic center (Leventhal, MacCallum, and Stang 1978; see also MacCallum and Leventhal 1983). It may also have been detected from gamma-ray burst sources (Teegarden and Cline 1980; Mazets *et al.* 1981) and from the Crab nebula (Leventhal, MacCallum, and Watts 1977; Hameury *et al.* 1983, and references therein). Future missions with more sensitive gamma-ray spectrometers will almost certainly lead to the discovery of new classes of annihilation-line sources. A number of astrophysical environments have been suggested as rich sources of positrons including the following: the magnetospheres of pulsars (e.g., Arons 1983), relativistic jets in compact radio sources (Noerdlinger 1978; Lovelace and Ruchti 1983), supernovae ejecta containing long-lived radioactive nuclei (Ramaty and Lingenfelter 1981), accretion disks around black holes (Eilek and Kafatos 1983), and possibly evaporating "mini" black holes (Okele and Rees 1980).

Another signature of a positron, which is poorly known compared with the 511 keV line, is the optical line spectrum produced when a positron and an electron combine to form positronium. Positronium, denoted by the symbol Ps, is analogous to the hydrogen atom and has a similar recombination spectrum. Two years after the discovery of the positron, Mohorovičić (1934) discussed its optical spectrum and suggested that it might be observed in stellar spectra. It seems that during the past 50 years, Mohorovičić's proposal has not been echoed in the literature, and there have been no other proposals to detect the recombination lines of positronium from celestial objects.

The structure of positronium is simple, and there never has been any serious doubt that eventually its optical spectrum would be observed in accordance with theory. Recently, favorable conditions were achieved in the laboratory; Canter, Mills, and Berko (1975) succeeded in efficiently producing positronium in a vacuum far from the radioactive positron source, and thereby made the first observation of the λ2430 Lyman-α line of positronium. In this paper we suggest that it may now be possible to detect the optical lines of positronium in the spectra of active galactic nuclei, pulsars, and other high-energy systems.

II. POSITRONIUM

For a wide range of temperature ($\lesssim 10^6$ K) and density ($n \lesssim 10^{14}\,\mathrm{cm}^{-3}$), most positrons first thermalize and then form positronium before annihilating (Crannell *et al.* 1976; Bussard, Ramaty, and Drachman 1979). The only competing process, free annihilation, is typically an order of magnitude less probable than the formation of positronium (Bussard, Ramaty, and Drachman 1979). In this section we discuss the atomic structure, decay, formation, and optical spectrum of positronium.

a) *Atomic Properties*

The wave function which describes the gross structure of positronium is the same as the wave function of atomic hydrogen if the electron mass, m, is replaced by the reduced mass, $m/2$, of the positron-electron system (e.g., Wheeler 1946). Consequently, the energy of the nth state of positronium is $E_n = -6.8/n^2$ eV, and the positron-electron separation in the ground state is twice the Bohr radius. The transition probabilities for dipole emission in positronium, for example, are half as great as the corresponding transition probabilities in hydrogen (Deutsch 1953). Of particular interest are the wavelengths of the Lyman, Balmer, and Paschen lines, which are twice the wavelengths of the corresponding hydrogen lines (Table 1).

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TABLE 1

RECOMBINATION LINES OF POSITRONIUM

Line	Wavelength (Å)	Relative Intensity[a]
Lyα.....	2431	32.7
Lyβ.....	2051	...
Lyγ.....	1985	...
Hα......	13126	2.9
Hβ......	9723	1.0
Hγ......	8681	0.47
Pα	37502	0.47
Pβ	25636	0.46
Pγ	21876	0.45

[a] Case A recombination for hydrogen (see § II*d*) at $T = 10{,}000$ K with no collisions (Osterbrock 1974).

b) *Annihilation*

The 511 keV annihilation line is produced by the two-photon decay of spherically symmetric S states. The lifetime of the ground singlet state is $T(^1S_0) = 1.25 \times 10^{-10}$ s (e.g., Deutsch 1953). Two-photon decay is completely forbidden for triplet S states, and their decay proceeds via three-photon annihilation. Thus, the lifetime of the ground triplet state is 1130 times longer, $T(^3S_1) = 1.41 \times 10^{-7}$ s (e.g., Deutsch 1953). For decay from excited states (singlet or triplet) with principal quantum number n and orbital angular momentum L, the lifetime is longer by a factor of the order of $n^3(e^2/\hbar c)^{-2L}$ (Massey, Burhop, and Gilbody 1974).

c) *Formation*

There are two competing processes which lead to the formation of positronium: (1) radiative recombination of free positrons and electrons, $e^+ + e^- \rightarrow \mathrm{Ps}$, and (2) charge exchange of positrons with neutral hydrogen, $e^+ + \mathrm{H} \rightarrow p + \mathrm{Ps}$ (Bussard, Ramaty, and Drachman 1979). The rate of radiative recombination is, of course, proportional to the electron density, whereas the rate of charge exchange is proportional to the density of neutral hydrogen. Consequently, the degree of ionization of the gas largely determines which process is dominant. In order to compare the two reaction rates directly, the rate coefficients (R/n) are given in Figure 1 in terms of the total gas density, $n = n_e + n_{\mathrm{H}}$. Two examples are considered: a collisionally ionized gas and a photoionized gas. The reaction rate ($\mathrm{cm^{-3}\ s^{-1}}$) for each process is the appropriate rate coefficient ($\mathrm{cm^3\ s^{-1}}$) times the total gas density ($\mathrm{cm^{-3}}$) times the number of density of free positrons ($\mathrm{cm^{-3}}$). The ratio of the reaction rates is proportional to the ratio of the rate coefficients. It is assumed that the positrons are in

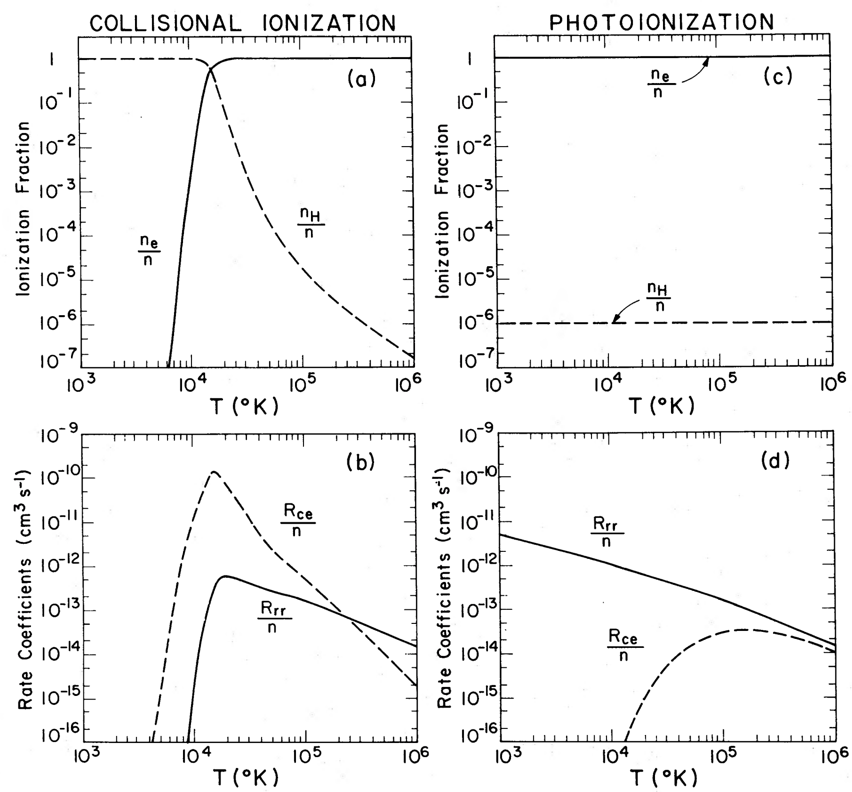

FIG. 1.—A comparison of the rates of the two processes which dominate the formation of positronium in two environments, a gas ionized by collisions and a photoionized gas. (*a*) The ionization equilibrium of hydrogen gas maintained by a balance between collisional ionization and radiative recombination. (*b*) The rate coefficients for positronium formation (Bussard, Ramaty, and Drachman 1979) in a collisonally ionized gas as a function of gas temperature or ionization state: R_{rr}/n is the total radiative recombination coefficient for positronium, and R_{ce}/n is the charge exchange coefficient for formation of positronium in the ground state. The inclusion of excited states may increase the value of R_{ce}/n (Bussard, Ramaty, and Drachman 1979, and references therein). (*c*) The ionization equilibrium of a photoionized gas (see text). At temperatures near 10^6 K, the gas will be more ionized than indicated in the figure because of collisions (cf. Fig. 1*a*). (*d*) The rate coefficients for positronium formation in a photoionized gas as a function of gas temperature or ionization state. Note that in this example radiative recombination is dominant at all temperatures. The total gas density is $n = n_e + n_{\mathrm{H}}$.

thermal equilibrium with the ambient environment (Crannell *et al.* 1976; Bussard, Ramaty, and Drachman 1979).[2]

The collisional ionization equilibrium (Fig. 1*a*) was computed by equating the rate of radiative recombination to the rate of collisional ionization for hydrogen (Seaton 1959; Cox and Tucker 1969; cf. Fig. 1 of House 1964). In this case, as shown in Figure 1*b*, the dominant mode of positronium formation for $T \lesssim 3 \times 10^5$ K is charge exchange. Many astrophysical plasmas, however, are significantly more ionized at a given temperature than indicated in the example in Figure 1*a* due to the presence of cosmic rays and ionizing photons (see, e.g., Osterbrock 1974; McKee and Ostriker 1977). For example, in Figure 1*c*, hydrogen gas is maintained with a small neutral fraction of 10^{-6} by a balance between photoionization and radiative recombination of hydrogen. The required flux of ionizing radiation in this case corresponds to the flux produced by a main-sequence O6 star ($T_* = 40{,}000$ K, $R = 9\ R_\odot$) at a distance of $d = 0.5/n$ pc, where $n \approx n_e$ is the total gas density (see, e.g., Osterbrock 1974; Underhill 1982). In this case, as shown in Figure 1*d*, the rate of positronium formation via radiative recombination is dominant at all temperatures $\lesssim 10^6$ K.

It seems likely that in many cases of interest the gas in which positrons thermalize and form positronium will be highly ionized by the radiation and particles emitted by the nearby positron source (pulsar, accreting black hole, etc.). Consequently, in the examples discussed in § III we assume that positronium is formed solely by radiative recombination. We note in passing that charge exchange will also result in the formation of excited states of positronium and the emission of optical line radiation; however, it seems that no work has been done on this probem (Bussard, Ramaty, and Drachman 1979, and references therein).

d) *Recombination Lines: Wavelengths, Intensities, and Widths*

The wavelengths of the leading lines of the Lyman, Balmer, and Paschen series of positronium are listed in Table 1. The relative intensities of the corresponding hydrogen lines, which are approximately the same as those of positronium, are also listed. The intensities are valid for a nebula which is optically thin in the Lyman lines (case A) and for which collisional effects are negligible. For the effects of collisions on the relative line strengths of atomic hydrogen, see Brocklehurst (1971), and for the effects of large optical depths, see, for example, Drake and Ulrich (1980).

The differences between the relative intensities of the positronium and hydrogen recombination lines are due to two effects. (1) The coefficient for radiative recombination onto level *n* for positronium divided by the corresponding recombination coefficient for hydrogen is a weak function of the principal quantum number *n*. For example, using Seaton's (1959) formulation with the electron mass *m* replaced by $m/2$, we find the following values for $\alpha(\mathrm{Ps})/\alpha(\mathrm{H})$ at $T = 10^4$ K: 2.73 for $n = 1$; 2.13 for $n = 5$; and 1.89 for the sum from $n = 6$ to infinity. (2) There is a smaller effect, caused by the annihilation of positronium, which also alters the relative line strengths of positronium relative to those of hydrogen. Excited *S* states of singlet positronium with principal quantum number *n* annihilate promptly in $n^3 1.25 \times 10^{-10}$ s (§ II*b*); in all cases, the lifetimes of the corresponding radiative atomic transitions (which are twice the corresponding values for atomic hydrogen given, for example, by Wiese, Smith, and Glennon 1966) are significantly longer. On the other hand, the annihilation lifetimes of excited triplet *S* states and all states with $L > 0$ are much longer than the allowed dipole lifetimes of the corresponding atomic states. Thus, only a small fraction of all states (25% of the states with $L = 0$) will annihilate before radiating. For example, given a statistical population of states (Brocklehurst 1971), the $n = 2$ level of positronium will be depopulated by annihilation by 6% relative to hydrogen, the $n = 3$ level by 3%, and all other levels by less than 2%. The two effects discussed here are not taken into account in Table 1 and are not considered further.

Positronium lines are Doppler broadened 30 times more than hydrogen lines for the same temperature: $(\Delta\lambda/\lambda)_{\mathrm{Ps}} = 1.30 \times 10^{-3}(T/10^4\ \mathrm{K})^{1/2}$. For example, the Ly$\alpha$ line suffers a broadening of 3 Å at 10^4 K and 30 Å at 10^6 K. It is important to note that the widths of the positronium lines are determined by the gas temperature in the annihilation region, and not by the initial velocities of the positrons (which may be ultra-relativistic). This is because the probability of annihilation in flight is small until the positrons are slowed to near-thermal energies (Bussard, Ramaty, and Drachman 1979).

III. POSSIBLE SOURCES OF POSITRONIUM RECOMBINATION LINES

Very limited information is available on the physical characteristics of the positron annihilation sites in the galactic center and in solar flares. No direct information is available in the case of pulsars, active galactic nuclei, etc. Therefore, in the examples discussed below it is arbitrarily assumed that the conditions are favorable for the production of positronium recombination lines, namely: (1) the fate of every positron is to radiatively combine with an electron to form positronium and then to annihilate promptly, and (2) the annihilation region and surrounding environment is optically thin as described in § II*d*.

These idealized assumptions permit the following simple derivation of the relationship between the Ps Lyα λ2430 and the 511 keV photon fluxes. The probability of emitting a Lyα photon following the recombination of a positron and an electron is about one-half. Based on the relative statistical weights of singlet and triplet positronium, only one-quarter of the positronium annihilation events yield a pair of 511 keV photons (§ II*b*). Thus, the Lyα λ2430 and 511 keV photon fluxes are about equal.

In the three examples which follow, only the feasibility of detecting the Ps Lyα line is considered; however, because of the relatively large extinction near λ2430, it may in fact prove more fruitful to search for the Balmer or Paschen lines. The capability of Space Telescope and the faint-object spectrograph (Leckrone 1980) is used as a benchmark for assessing the feasibility of detecting the Ps Lyα line; an overall efficiency (telescope, spectrograph, and Digicon detector) near λ2430 of 5% is assumed.

a) *Galactic Center*

A 511 keV positron annihilation line has been observed from the galactic center for more than a decade (e.g., MacCallum and Leventhal 1983). The size of the 511 keV

[2] It is also possible for positronium to form in flight via charge exchange in a largely neutral medium ($n_{\mathrm{H}}/n \gtrsim 0.5$) such as a molecular cloud (Bussard, Ramaty, Drachman 1979). In this case, the optical lines may be significantly broadened by the suprathermal motion of the positronium (Crannell *et al.* 1976), and therefore more difficult to detect.

emission region has been inferred from variations in the line strength to be $\lesssim 10^{18}$ cm ($\lesssim 7''$). The line is narrow (FWHM < 2.5 keV) and unredshifted (Riegler *et al.* 1981). The observed 511 keV flux is typically about 2×10^{-3} photons cm^{-2} s^{-1}, which corresponds to a positron annihilation rate of approximately 4×10^{43} s^{-1} (Lingenfelter and Ramaty 1983).

The positron source at the galactic center is presently the only confirmed, nonsolar source of annihilation-line radiation. Unfortunately, the prospects of detecting positronium recombination lines from this source are bleak. The visual extinction to the galactic center is $A_v \sim 30$ mag, and the extinction at Ps Hα λ13126 is approximately 7 mag (Becklin *et al.* 1978).[3] For the purposes of illustration, however, we ignore the extinction. In this case, the Ps Lyα flux at Earth is about the same as the 511 keV flux (see above), namely, $F(\text{Ps Ly}\alpha) \sim 2 \times 10^{-3}$ photons cm^{-2} s^{-1}. In observational terms, this flux corresponds to a Ps Lyα emission line with an equivalent width of 10 Å relative to a continuum with $m_{2430} = 16$ mag.[4] This is an intense line and could be detected (5 σ) by Space Telescope (see above) in about 10 s. This estimate is based on a point source, a line width of 10 Å, a spectrograph slit width of 0."3, and a sky background which is not brighter than about 13 mag arcsec^{-2}. (The dark sky background is about 26 mag arcsec^{-2}.) By comparison, the first convincing observation of the 511 keV line from the galactic center by the Bell/Sandia group required 17 hours of observing time to achieve a comparable level of statistical significance, 5.5 σ (Leventhal, MacCallum, and Stang 1978).

The hypothetical example above illustrates that if the optical extinction and background continuum flux are moderate, and if the assumptions stated at the outset of this section are valid, then a detectable source of 511 keV photons should also be a detectable source of λ2430 photons. Moreover, the example suggests that for some celestial positron sources it may be easier to detect the optical lines than to detect the 511 keV line.

b) Active Galactic Nuclei

As pointed out by Lingenfelter and Ramaty (1982), the luminosity of the annihilation radiation from the galactic center, approximately 10^{38} ergs s^{-1}, is comparable to the most intense emission directly observed at any wavelength from compact sources located there. The presence of such a strong positron source in the prosaic nucleus of our Galaxy is a remarkable fact, and it suggests that active galactic nuclei (AGNs) may be very luminous annihilation-line sources. The 511 keV line has not yet been detected from any AGN (Marscher *et al.* 1983); however, its intensity due to photon-photon pair production can be estimated if the gamma-ray continuum near 1 MeV is known (Lingenfelter and Ramaty 1982; Guilbert, Fabian, and Rees 1983). Matteson (1983) used this approach to predict annihilation-line intensities for several AGNs. For the most favorable case, NGC 4151, Matteson estimates a 511 keV flux of approximately 1×10^{-3} photons cm^{-2} s^{-1}, which corresponds to a 511 keV line luminosity of 1×10^{43} ergs s^{-1} for a distance of 11 Mpc. Ignoring the extinction in NGC 4151, the expected Ps Lyα flux at Earth is also about 1×10^{-3} photons cm^{-2} s^{-1} (see above). Can a line of this strength be detected in the presence of the optical continuum from the nucleus of NGC 4151 near λ2430? The continuum flux from the nucleus is approximately 8×10^{-3} photons cm^{-2} s^{-1} Å^{-1} (Wu and Weedman 1978). For an assumed line width of 10 Å, the line is about 1.3% above the continuum and could be detected (5 σ) in 15 minutes with Space Telescope (see above). This is an optimistic estimate for at least two reasons. First, there is considerable structure in the spectra of AGNs near Ps Lyα due to a blend of Fe II emission lines (Wills *et al.* 1980; Grandi 1981). Second, the extinction in NGC 4151 (Wu, Boggess, and Gull 1980) and AGNs generally (Davidson and Netzer 1979) is not negligible. In fact, the extinction as evidenced by the relative strengths observed for the hydrogen lines in AGNs suggests that it may be easier to detect the Balmer or Paschen lines of positronium than to detect the Lyman lines.

The positronium Lyα line falls in the visible for QSOs of moderate redshift $0.5 \lesssim z \lesssim 2.0$. An examination of 25 published QSO spectra (*Ap. J.*, 1978–1981) with coverage at Ps Lyα λ2430 revealed three QSOs which have moderately interesting features centered at λ2430 which rise a few percent above the continuum: Ton 490 (Baldwin and Netzer 1978), PKS 1252+119, and PKS 2344+092 (Grandi 1981). In each case, the feature is located in a blend of Fe II emission lines; however, several different models of the Fe II emission in QSOs (see Fig. 2 of Grandi 1981) indicate that no major Fe II feature is expected at λ2430.

In conclusion, it may be possible to achieve a convincing detection of the optical lines of positronium in the spectra of QSOs and Seyfert galaxies. However, it probably will not be an easy task because the compact nuclei of AGNs are very luminous, and because current models of AGNs cannot account for many details observed in their spectra.

c) Crab Pulsar

In most pulsar models, the creation of positron-electron pairs plays an essential role in the magnetospheric dynamics and the production of the observed coherent radio emission (Sturrock 1971; Ruderman and Sutherland 1975; Arons 1983, and references therein). There has not yet been, however, a convincing detection of 511 keV positron annihilation radiation from pulsars (with due respect to Leventhal, MacCallum, and Watts 1977). Sturrock and Baker (1979) have estimated the rate of positron production by the Crab pulsar to be approximately 1×10^{41} positrons s^{-1}, which corresponds to a 511 keV line flux of 4×10^{-4} photons cm^{-2} s^{-1} (for $d_{\text{Crab}} = 2$ kpc). We note that this predicted flux would have escaped detection in past observations of the Crab pulsar (Leventhal, MacCallum, and Watts 1977; Ling *et al.* 1977; Hameury *et al.* 1983).

As discussed above, the predicted Ps Lyα flux in the absence of extinction is also 4×10^{-4} photons cm^{-2} s^{-1}. The interstellar extinction of the Crab pulsar at the wavelength of Ps Lyα is $A_{2430} \approx 3.9$ mag (Wu 1981). Thus, the predicted Ps Lyα flux at Earth is approximately 1.1×10^{-5} photons cm^{-2} s^{-1}. The continuum flux near λ2430 due to the pulsar is $F_{2430} \approx 1.2 \times 10^{-4}$ photons cm^{-2} s^{-1} Å^{-1} (Kristian *et al.* 1970). The predicted equivalent width of the Lyα line is therefore 0.1 Å; for an assumed line width of 10 Å, the flux in the line is 1% of the continuum flux. To achieve a formal detection (5 σ) of the line with Space Telescope (see above) would require a net observing time of 1 day.

Therefore, based on Sturrock and Baker's (1979) estimates, it appears that it may be possible to detect the Ps Lyα line

[3] The extinction for the Paschen lines, however, is moderate. The Ps Pα extinction, for example, is $A(37502) \sim 1.3$ mag (Becklin *et al.* 1978).

[4] The magnitude m_λ is defined to be 0.000 mag when $F_\lambda = 3.64 \times 10^{-9}$ ergs cm^{-2} s^{-1} Å^{-1} (Oke and Schild 1970).

from the Crab pulsar. On the other hand, the pulsar models developed by Cheng and Ruderman (1977) and Scharlemann, Arons, and Fawley (1978) predict a positron flux for the Crab pulsar which is lower by several orders of magnitude.

IV. CONCLUSION

The *in situ* presence of electrons in astrophysics was established early in this century by observations of the radiation they emit. The presence of nonsolar positrons, on the other hand, was demonstrated only recently by the detection of the 511 keV positron annihilation line from the galactic center. If it were not for the severe interstellar extinction, optical lines of positronium might also be observed from the galactic center. For example, in the absence of extinction, a secure detection of the Ps Lyα λ2430 line might require only about 10 s of observing time with Space Telescope (see § III*a*). By comparison, the detection of the 511 keV line from the galactic center achieved by Leventhal, MacCallum, and Stang (1978) required 17 hours of observing time.

The predicted annihilation-line fluxes for a number of Seyfert galaxies, QSOs, and pulsars are near the detection threshold of today's gamma-ray spectrometers. It may prove fruitful to examine the optical spectra of these objects for the presence of positronium recombination lines. The Ps Lyα λ2430 line may already be in evidence in published spectra of moderate redshift QSOs (§ III*b*). The equivalent width of the Ps Lyα line in the spectra of NGC 4151 and the Crab pulsar is estimated in § III to be about 100 mÅ, which should be observable with Space Telescope.

In conclusion, for the model discussed in § II*d* we note that approximately 1–2 mag of visual extinction are sufficient to make the Balmer or Paschen lines of positronium more intense than the Lyman-α line (Table 1; Becklin *et al.* 1978; Wu 1981). Therefore, if a source is moderately reddened (e.g., the Crab pulsar), the best strategy may be to search for the Balmer or Paschen lines. This conclusion depends, of course, on several additional factors including the spectrum of background light from the source and the sensitivity of available instrumentation.

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REFERENCES

Arons, J. 1983, in *Positron-Electron Pairs in Astrophysics*, ed. M. Burns, A. Harding, and R. Ramaty (New York: AIP), p. 163.
Baldwin, J. A., and Netzer, H. 1978, *Ap. J.*, **226**, 1.
Becklin, E. E., Matthews, K., Neugebauer, G., and Willner, S. P. 1978, *Ap. J.*, **220**, 831.
Brocklehurst, M. 1971, *M.N.R.A.S.*, **153**, 471.
Bussard, R. W., Ramaty, R., and Drachman, R. J. 1979, *Ap. J.*, **228**, 928.
Canter, K. F., Mills, A. P., Jr., and Berko, S. 1975, *Phys. Rev. Letters*, **34**, 177.
Cheng, A. F., and Ruderman, M. A. 1977, *Ap. J.*, **216**, 865.
Cox, D. P., and Tucker, W. H. 1969, *Ap. J.*, **157**, 1157.
Crannell, C. J., Joyce, G., Ramaty, R., and Werntz, C. 1976, *Ap. J.*, **210**, 582.
Curie, I., and Joliot, F. 1933, *J. de Phys.*, **4**, 494.
Davidson, K., and Netzer, H. 1979, *Rev. Mod. Phys.*, **51**, 715.
Deutsch, M. 1953, *Prog. Nuc. Phys.*, **3**, 131.
Drake, S. A., and Ulrich, R. K. 1980, *Ap. J. (Suppl.)*, **42**, 351.
Eilek, J. A., and Kafatos, M. 1983, *Ap. J.*, **271**, 804.
Grandi, S. A. 1981, *Ap. J.*, **251**, 451.
Guilbert, P. W., Fabian, A. C., and Rees, M. J. 1983, *M.N.R.A.S.*, **205**, 593.
Hameury, J. M., Boclet, D., Durouchoux, Ph., Cline, T. L., Paciesas, W. S., Teegarden, B. J., Tueller, J., and Haymes, R. C. 1983, *Ap. J.*, **270**, 144.
House, L. L. 1964, *Ap. J. Suppl.*, **8**, 307.
Kristian, J., Visvanathan, N., Westphal, J. A., and Snellin, G. H. 1970, *Ap. J.*, **162**, 475.
Leckrone, D. S. 1980, *Pub. A.S.P.*, **92**, 5.
Leventhal, M. MacCallum, C. J., and Stang, P. D. 1978, *Ap. J. (Letters)*, **225**, L11.
Leventhal, M., MacCallum, C., and Watts, A. 1977, *Ap. J.*, **216**, 491.
Ling, J. C., Mahoney, W. A., Willett, J. B., and Jacobson, A. S. 1977, *Nature*, **270**, 36.
Lingenfelter, R. E., and Ramaty, R. 1982, in *The Galactic Center*, ed. G. R. Riegler and R. D. Blandford (New York: AIP), p. 148.
———. 1983, in *Positron-Electron Pairs in Astrophysics*, ed. M. Burns, A. Harding, and R. Ramaty (New York: AIP), p. 267.
Lovelace, R. V. E., and Ruchti, C. B. 1983, in *Positron-Electron Pairs in Astrophysics*, ed. M. Burns, A. Harding, and R. Ramaty, (New York: AIP), p. 314.
MacCallum, C. J., and Leventhal, M. 1983, in *Positron-Electron Pairs in Astrophysics*, ed. M. Burns, A. Harding, and R. Ramaty (New York: AIP), p. 211.
Marscher, A. P., Brecher, K., Wheaton, W. A., Ling, J. C., Mahoney, W. A., and Jacobson, A. S. 1983, in *Positron-Electron Pairs in Astrophysics*, ed. M. Burns, A. Harding, and R. Ramaty (New York: AIP), p. 303.
Massey, H. S. W., Burhop, E. H. S., and Gilbody, H. B. 1974, *Electronic and Ionic Impact Phenomena* (Oxford: Clarendon), Vol. **5**, p. 3123.
Matteson, J. L., 1983, in *Positron-Electron Pairs in Astrophysics*, ed. M. Burns, A. Harding, and R. Ramaty (New York: AIP), p. 292.
Mazets, E. P., Golenetskii, S. V., Aptekar', R. L., Gur'yan, Yu. A., and Il'inskii, V. N. 1981, *Nature*, **290**, 378.
McKee, C. F., and Ostriker, J. P. 1977, *Ap. J.*, **218**, 148.
Mohorovičić, S. 1934, *Astr. Nach.*, **253**, 94.
Noerdlinger, P. D. 1978, *Phys. Rev. Letters*, **41**, 135.
Oke, J. B., and Schild, R. E. 1970, *Ap. J.*, **161**, 1015.
Okele, P. N., and Rees, M. J. 1980, *Astr. Ap.*, **81**, 263.
Osterbrock, D. E. 1974, *Astrophysics of Gaseous Nebulae* (San Francisco: Freeman).
Ramaty, R., and Lingenfelter, R. E. 1981, *Phil. Trans. Roy. Soc. London*, **A301**, 671.
Riegler, G. R., Ling, J. C., Mahoney, W. A., Wheaton, W. A., Willett, J. B., Jacobson, A. S., Prince, T. A. 1981, *Ap. J. (Letters)*, **248**, L13.
Ruderman, M. A., and Sutherland, P. G. 1975, *Ap. J.*, **196**, 51.
Scharlemann, E. T., Arons, J., and Fawley, W. M., 1978, *Ap. J.*, **222**, 297.
Seaton, M. J. 1959, *M.N.R.A.S.*, **119**, 81.
Share, G. H., Chupp, E. L., Forrest, D. J., and Rieger, E. 1983, in *Positron-Electron Pairs in Astrophysics*, ed. M. Burns, A. Harding, and R. Ramaty (New York: AIP), p. 15.
Sturrock, P. A. 1971, *Ap. J.*, **164**, 529.
Sturrock, P. A., and Baker, K. B. 1979, *Ap. J.*, **234**, 612.
Teegarden, B. J., and Cline, T. L. 1980, *Ap. J. (Letters)*, **236**, L67.
Thibaud, J. 1933*a*, *C.R. Acad. Sci., Paris*, **197**, 447.
———. 1933*b*, *C.R. Acad. Sci., Paris*, **197**, 915.
———. 1933*c*, *C.R. Acad. Sci., Paris*, **197**, 1629.
Underhill, A. B. 1982, *Ap. J.*, **263**, 741.
Wheeler, J. A. 1946, *Ann. NY Acad. Sci.*, **48**, 219.
Wiese, W. L., Smith, M. W., and Glennon, B. M. 1966, *Atomic Transition Probabilities*, Vol. **1** (NSRDS-NBS 4).
Wills, B. J., Netzer, H., Uomoto, A. K., and Wills, D. 1980, *Ap. J.*, **237**, 319.
Wu, C.-C. 1981, *Ap. J.*, **245**, 581.
Wu, C.-C., Boggess, A., and Gull, T. R. 1980, *Ap. J.*, **242**, 14.
Wu, C.-C., and Weedman, D. W., 1978, *Ap. J.*, **223**, 798.

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