Space positronium detection by radio measurements

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Abstract

The possibility of positronium detection at radio wavelengths is investigated in detail. For orthopositronium, the fine structure lines of the \( n = 2 \) level (1.62 cm, 2.30 cm and 3.48 cm) may be probably detected by radiotelescopes of next generations with the sensitivity around 1 µJy. The spin-flip line of the ground state (0.147 cm) may be observed from sources with a narrow annihilation line by modern telescopes with the sensitivity around 10 µJy. In the fine structure and spin-flip lines a maser effect is produced. The expected radio fluxes in the spin-flip line can reach detected limits for certain source geometries and optimal physical conditions inside the source.

Keywords: formation - masers - radiative transfer - radio lines: general.

Introduction

The development of X-ray and \( \gamma \)-ray astronomy over the last ten years has shown that the \((e^+e^-)\) annihilation process is exceptionally important in modern astrophysics; the presence in space of processes leading to creation of positrons has been unambiguously confirmed. However, a narrow 511 KeV line has only been detected in the Galactic center region (Teegarden, 1994; Cheng et al., 1997; Purcell et al., 1997; Teegarden et al., 1997 and Smith,
Purcell, Leventhal, 1997). There are some sources, e.g. 1E 1740.7-2942, Nova Muscae, and the Crab, whose spectra display bright transient emission features near 0.5 MeV (see the review of Smith et al., 1996). As theoretical analysis has shown, positron annihilation proceeds mainly via positronium states if the temperature of the annihilation medium is low (Gould, 1989; Guessoum, Ramaty, Lingenfelter, 1991; Burdyuzha and Kauts, 1995 [hereafter BK]).

The probability of positronium detection in the UV ($\lambda = 2431\text{ Å}$) and IR ($\lambda = 1.31\mu m, 3.75\mu m$) regions has been considered in detail in our previous articles (Burdyuzha, Kauts, and Yudin, 1992; Burdyuzha, Kauts, and Wallyn, 1996). Here we consider the possibility of observing the radio line triplet at 8625 MHz (3.48 cm), 13010 MHz (2.30 cm), and 18496 MHz (1.62 cm), corresponding to the fine structure of the orthopositronium $n = 2$ level and the spin-flip line at 203387 MHz (0.147 cm) of the hyperfine structure of the ground state.

Since the observed narrow annihilation line sources are located in the Galactic Center region where the absorption at UV and IR wavelengths is high, the study of positronium detection at radio wavelengths is very important.

Positronium atom

The simplest positronium atom consists of an electron $e^-$ and a positron $e^+$, and can exist in two states – parapositronium with zero total spin of its electron and positron, and orthopositronium with the total spin equal to unity (see Fig. 1). The main distinction between a positronium and a hydrogen atom lies in the fact that in states with zero orbital momentum positronium is an unstable atomic system with lifetimes in the orthostate $\tau_{ortho} \simeq 1.33 \times 10^{-7} n^3\text{ sec}$ and in the parastate $\tau_{para} \simeq 1.25 \times 10^{-10} n^3\text{ sec}$ (here $n$ is the principal quantum number). Also shown in Fig. 1 are the fine and hyperfine structure of the lower levels of positronium. As in the case of the hydrogen atom, the formation of positronium in an excited state leads to an electromagnetic cascade to lower levels and to appearance of characteristic lines ($L_\alpha, L_\beta..., H_\alpha, H_\beta..., P_\alpha, P_\beta...$).

The lifetimes of lower states to annihilation are very short, so for low densities an equilibrium population of levels has no time to form and populations are determined by processes of recombination or charge exchange followed by a radiative cascade and annihilation. In these conditions the appearance of maser radiation seems natural.
Positronium atoms are produced after the delay of positrons. The probability of positronium formation on one positron ($f$) depends essentially on the parameters of the medium (its temperature, the presence of dust, and so on). The value of $f$ in different media has been estimated by many authors (e.g. Bussard, Ramaty, and Drachman, 1979) and is $\sim 0.9 \div 0.95$. For the case of an ionized hydrogen medium the rate of radiative capture in the process $e^+ + e^- \rightarrow Ps + \gamma$ is higher than the rate of direct annihilation $e^+ + e^- \rightarrow 2\gamma$ at temperatures $< 10^6$ K (Gould, 1989). For the case of an atomic or molecular hydrogen medium an energetic positron, after entering the medium, effectively loses its energy by ionization and excitation of atoms and molecules of hydrogen and by Coulomb collisions. In this case annihilation processes proceed at low energies and positronium atoms will be formed at these energies by charge exchange reactions before annihilation.

For astrophysical applications it is important that the formation of excited states of positronium be suppressed (BK). Therefore transitions between lower levels are more promising for observations.

Radio lines of the orthopositronium $n=2$ fine structure level

The triplet of radio lines corresponding to $n = 2$ fine structure transitions may appear for radiative transitions $2^3S_1 \rightarrow 2^3P_i$ ($i = 0, 1, 2$) (see Fig 1). The lifetime of the $2^3S_1$ level is determined by three-photon annihilation $\tau(2^3S_1) = 1.1\mu s$ while the lifetimes of the $2^3P_i$ levels are determined by the $L_\alpha$ transition $\tau(2^3P_i) = 3.2ns$. It is easy to see that a strong overpopulation of the $2^3S_1$ level is created and that maser emission takes place in this triplet.

The one-dimensional radiative transfer equation of in a line of this triplet is:

$$\frac{dI^i_{\nu}}{dx} = \frac{h\nu_i}{\Delta\nu_i} \left[ \dot{n}_{ps}(2^3S_1) \frac{A(2^3S_1 \rightarrow 2^3P_i)/4\pi + B(2^3S_1 \rightarrow 2^3P_i)I^i_\nu/c}{A(2^3S_1 \rightarrow 2^3P_i) + \sum B(2^3S_1 \rightarrow 2^3P_i)I^i_\nu\Delta\Omega_i/c + W^{3\gamma}_{\text{annih.}}} ight] \left[ \dot{n}_{ps}(2^3P_i) \frac{B(2^3P_i \rightarrow 2^3S_1)I^i_\nu/c}{B(2^3P_i \rightarrow 2^3S_1)I^i_\nu\Delta\Omega_i/c + A_{L_\alpha}} \right], \quad i = 0, 1, 2$$

(1)

where $I^i_\nu$ is the intensity in one of the lines of the triplet; $\dot{n}_{ps}$ is the rate of positronium formation in the respective states per unit volume; $A(2^3S_1 \rightarrow 2^3P_i)$ are the probabilities of spontaneous transitions $5.71 \times 10^{-6} s^{-1}$, $5.96 \times 10^{-6} s^{-1}$, and $2.89 \times 10^{-6} s^{-1}$ in levels $2^3P_0, 2^3P_1,$
and $2^3P_2$, respectively, and $B_i$ are the Einstein coefficients. $\Delta\Omega_i$ is the degree of background anisotropy; $W_{\text{annih.}}^{3\gamma}$ is the probability of three-photon annihilation with the $2^3S_1$ level and $A_{L\alpha}$ is the probability of the $L\alpha$ transition.

In this expression collisional processes are not included since densities in the annihilation region are low. For the case of ionized hydrogen this leads to the limit $n \lesssim 10^9 \sqrt{T_{\text{eV}}} \text{ cm}^{-3}$, where $T$ is the Maxwell temperature of ionized hydrogen (Burdyuzha, Kauts, and Yudin, 1992). For the case of atomic and molecular hydrogen our approximation will be valid over a wider range of densities.

Since for any physical conditions the inequality $A(2^3S_1 \rightarrow 2^3P_i)/4\pi \ll B(2^3S_1 \rightarrow 2^3P_i)I_\nu^i/c$ holds, we obtain:

$$\frac{dI^i_\nu}{dx} = \frac{h\nu_i}{\Delta\nu_i} \left[ \dot{n}_{ps}(2^3S_1) \sum_{i=0,1,2} \frac{B(2^3S_1 \rightarrow 2^3P_i)I^i_\nu/c}{B(2^3S_1 \rightarrow 2^3P_i)I^i_\nu \Delta\Omega_i/c + W_{\text{annih.}}^{3\gamma}} - \dot{n}_{ps}(2^3P_i) \frac{B(2^3P_i \rightarrow 2^3S_1)I^i_\nu/c}{B(2^3P_i \rightarrow 2^3S_1)I^i_\nu \Delta\Omega_i/c + A_{L\alpha}} \right], \ i = 0, 1, 2 \ (2)$$

For the conditions $B(2^3S_1 \rightarrow 2^3P_i)I^i_\nu \Delta\Omega_i/c \approx W_{\text{annih.}}^{3\gamma}$, a transition from the unsaturated to the saturated regime takes place. The respective brightness temperatures are $T_{b}^{i\text{,cr.}} = (1.5, 1.0, \text{and} 1.3) \times 10^{11} (\frac{4\pi}{\Delta\Omega_i}) \text{ K}$. In the subsequent discussion we consider three possible cases.

1) $T_b < T_{b}^{i\text{,cr.}}$ (that is, the maser regime is not saturated). The probability of positronium production in the $2S, 2P$ states in different media has been considered many times (Nahar, 1984; Hewitt et al., 1990; Biswas et al., 1991). Since $A_{L\alpha} \gg W_{\text{annih.}}^{3\gamma}$ and the formation rates $\dot{n}_{ps}(2^3S_1)$ and $\dot{n}_{ps}(2^3P_i)$ differ insignificantly for positronium formation energies (BK), so $\frac{\dot{n}_{ps}(2^3S_1)}{W_{\text{annih.}}^{3\gamma}} \gg \frac{\dot{n}_{ps}(2^3P_i)}{A_{L\alpha}}$ and equation (2) takes the form:

$$\frac{dI^i_\nu}{dx} = \frac{h\nu_i}{\Delta\nu_i} \left[ \dot{n}_{ps}(2^3S_1) \frac{1}{W_{\text{annih.}}^{3\gamma}} B(2^3S_1 \rightarrow 2^3P_i)I^i_\nu/c \right]$$

The corresponding depths $\tau_i$ are:

$$\tau_i = \frac{h\nu_i}{\Delta\nu_i} \dot{n}_{ps}(2^3S_1) \frac{1}{W_{\text{annih.}}^{3\gamma}} A(2^3S_1 \rightarrow 2^3P_i) \frac{c^2}{8\pi h\nu_i^3} l, \ i = 0, 1, 2 \ (3)$$
where $l$ is a characteristic dimension of the annihilation region.

Thus we see that $\tau_i \sim A_i/\nu_i^3 \sim (2J_i + 1)$, that is $\tau_0 : \tau_1 : \tau_2 = 1 : 3 : 5$.

As the simplest example, we consider a spherical annihilation line source radiating isotropically which has dimension $l$ at a distance $R$ from the observer. We take $\dot{n}_{ps}(2^3S_1) \simeq \dot{n}_{ps}(1^3S_1)/8$ (for the case of ionized hydrogen the asymptotic behaviour of these values was investigated by Burdyuzha et al. (1992); for atomic and molecular hydrogen the detail analysis and the rationale for choosing this approximation was presented by BK). Then for the most intense line $2^3S_1 \rightarrow 2^3P_2$ ($\nu_2 = 8625$ MHz) the optical depth $\tau_2$ is

$$\tau_2 \approx 5 \times 10^{-5} \left( \frac{0.75f}{2 - 1.5f} \right) \left( \frac{F_{511}^{511}}{10^{-4} \text{ph/cm}^2\text{s}} \right) \left( \frac{R}{10 \text{ kpc}} \right)^2 \left( \frac{l}{1 \text{ a.u.}} \right)^{-2} \tag{4}$$

for $\Delta \nu/\nu \sim 1/200$ (the width depending on the motion of positronium atoms (Teegarden, 1994 and BK) and the intrinsic line width are of the same order). The value of $\left( \frac{0.75f}{2 - 1.5f} \right) \sim 1 - 1.2$ for $f \sim 0.9 - 0.95$.

2) If $T_b > T_b^{i,cr}$, the maser regime is saturated and its main characteristic will be a spectral flux density. In this case the ratios of the spectral flux densities depend on the values of $B(2^3S_1 \rightarrow 2^3P_i) I_\nu I_\Delta \Omega_i$. The total photon fluxes in the lines of the triplet are determined only by the rate of positronium formation in the $2^3S_1$ state:

$$F_\nu^i = \frac{\dot{n}(2^3S_1)l^3 h \nu_i B_i I_\nu I_\Delta \Omega_i}{24R^2 \Delta \nu_i \sum B_i I_\nu I_\Delta \Omega_i} \left( \frac{4 \pi}{\Delta \Omega_{F_i}} \right)$$

where $\Delta \Omega_{F_i}$ is the anisotropy of the radio emission from the annihilation region in the respective line. As an example, for a flat spectrum and $\Delta \Omega_i \simeq \text{constant}$ we have:

$$F_\nu(2^3S_1 \rightarrow 2^3P_2) \approx 0.001 \left( \frac{0.75f}{2 - 1.5f} \right) \left( \frac{F_{511}^{511}}{10^{-4} \text{ph/cm}^2\text{s}} \right) \left( \frac{4 \pi}{\Delta \Omega_{F_2}} \right) \text{mJy} \tag{6}$$

3) For very high temperatures $T_b > T_b^{i,high} = (1.6, 3.3, \text{and 7.4}) \times 10^{13} \left( \frac{4 \pi}{\Delta \Omega_i} \right) K$ determined by conditions $B(2^3P_i \rightarrow 2^3S_1) I_\nu I_\Delta \Omega_i/c \approx A_{Lo}$, induced transitions dominate. Therefore the ratios of the spectral flux densities are $F_\nu^0 : F_\nu^1 : F_\nu^2 \simeq 1 : 3 : 5$. For $T_b \geq T_b^{i,high}$ line broadening due to induced transitions is the most important effect and an following increase
in temperature results in overlapping lines. The spectral flux densities in this regime will also be determined by formula (6) but it is necessary to take the increase in line widths into account adding the coefficient $\sim \left(T_{b,\text{high}}/T_b\right)$ to this formula.

In parapositronium the situation is more complex since the lifetimes of the levels $\tau(2^1P_1) \approx \tau(2^1S_0)$ and accurate predictions require further study.

The positronium spin-flip radio line

The hyperfine structure transition $1^3S_1 \rightarrow 1^1S_0$ of the ground state (spin-flip line) and the fine structure transitions can be observed in emission since the lifetime of the level $1^3S_1(\tau = 1.33 \times 10^{-7} \text{ sec})$ is much longer than the lifetime of the $1^1S_0$ level ($\tau = 1.25 \times 10^{-10} \text{ sec}$). Here the maser effect is also evident. This transition is of the $M1$ type with $\nu = 203387 \text{ MHz}$, $A = 3.37 \times 10^{-8} \text{ s}^{-1}$ and intrinsic line width $\Delta \nu = 1.3 \times 10^9 \text{ Hz}$. We have repeated the analysis for the spin-flip line similar to previous one. The transition from the unsaturated to the saturated regime occurs for $B(1^3S_1 \rightarrow 1^1S_0) I_{\nu} \Delta \Omega/c \approx \mathcal{W}_{\text{annih},1^3S_1}^\gamma$. The corresponding brightness temperature is $T_{b,\text{cr}} = 2.2 \times 10^{15} \left(\frac{4\pi}{4M}\right) K$. The optical depth in the unsaturated regime for the conditions described in formula (4) is

$$\tau \approx 5 \times 10^{-11} \left(\frac{0.75 f}{2 - 1.5 f}\right) \left(\frac{F_{511}^{\nu}}{10^{-4} \text{ ph/cm}^2 \text{s}}\right) \left(\frac{R}{10 \text{ kpc}}\right)^2 \left(\frac{l}{1 \text{ a.u.}}\right)^{-2}$$

(7)

The spectral flux density in saturated regime from an annihilation region is

$$F_{\nu} \approx 0.013 \left(\frac{0.75 f}{2 - 1.5 f}\right) \left(\frac{F_{511}^{\nu}}{10^{-4} \text{ ph/cm}^2 \text{s}}\right) \left(\frac{4\pi}{\Delta \Omega F_{\nu}}\right) \text{ mJy}$$

(8)

The width depending on the motion of Ps atoms (Teegarden, 1994; BK) and the intrinsic line width are of the same order just as in the case of the fine structure lines.

If $T_b \geq T_{b,\text{high}} = 7.7 \times 10^{17} \left(\frac{4\pi}{4M}\right) K$, which is determined by the condition $B(1^1S_0 \rightarrow 1^3S_1) I_{\nu} \Delta \Omega/c \approx \mathcal{W}_{\text{annih},1^1S_0}^{2\gamma}$, then the spectral flux density in this regime will also be given by formula (8) but due to the increase of the line width the coefficient $(3T_{b,\text{high}}^\text{high}/4T_b)$ appears.

Conclusions
Simultaneous observations of triplet radio lines can solve the problem of positronium identification. It follows from equation 4 that observations of such lines in the unsaturated regime are possible only from sufficiently compact and distant sources with the large flux in an annihilation line. Today such sources are unknown. From equation 6, the spectral flux densities in the saturated regime are just detectable with modern radio telescopes for
\[
\left( \frac{F_{511}}{10^{-4} \text{ph/cm}^2 \text{s}} \right) \left( \frac{4\pi}{\Delta \Omega F_2^2} \right) \geq 1.
\]
Note that formula 6 gives the total spectral flux density from the entire annihilation region, and that the flux may be larger if the source is anisotropic. But it is certainly an unnatural proposal.

For the spin-flip line the optical depth in the unsaturated regime is very small since this is the M1 type transition and it is impossible to detect. But the situation is different in the saturated regime. The spectral flux density in the saturated regime is higher than that in the triplet lines (equation 8) but the point of transition from the unsaturated to the saturated regime \( T_{cr} \) is shifted. As was shown by Kardashev (1979), this transition is optimal for interstellar communication but so far attempts to observe possible planetary systems at 203387 MHz have not been successful (Mauersberger et al., 1995). It is very desirable to extend these observations to possible sources of the 511 keV annihilation line with high brightness temperatures in the mm range (radio jets sources, radiopulsars and so on). The search for this radio line can be done in the direction of the Galactic center but to date a narrow annihilation line point source has not been detected there, so the exact predictions cannot be done. One promising source for spin-flip detection is radiopulsars. The problem is a difficult one, since necessary conditions are the presence of positrons (e.g., in a pulsar wind), and an appropriate deceleration length; a medium with a define density and dimension is required.

In addition to radio observations positronium can be also detected in the recombination lines \( L_\alpha (2431 \AA) \), \( H_\alpha (1.31 \mu m) \) and \( P_\alpha (3.75 \mu m) \). This possibility was investigated in our previous articles (Burdyuzha, Kants, and Yudin, 1992; BK; Burdyuzha, Kauts, and Wallyn, 1996). The \( L_\alpha \) line is difficult to observe in the direction of the Galactic center because of high absorption but it may be observed from active galactic nuclei with UV bumps in their spectra and from new point sources in our Galaxy which have to be detected. Observations of \( L_\alpha (2431 \AA) \) can be carried out with the HST. The IR lines \( H_\alpha (1.31 \mu m) \), \( H_\beta (0.97 \mu m) \) and \( P_\alpha (3.75 \mu m) \) can be observed by Keck telescope and probably by UKIRT, IRTF IR telescopes.
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Lower levels of positronium (the splitting of the n=3 level is not indicated)