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X-ray polarization in the two-phase model for AGN and X-ray binaries

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ABSTRACT

We calculate the polarization properties of the two-phase model proposed by Haardt & Maraschi to explain the X-ray emission of AGN and X-ray binaries. In this model, hot electrons in an optically thin corona Comptonize the soft photons emitted by the underlying accretion disc to produce the X-rays. We find that the degree of polarization depends strongly on the inclination angle of the system, on the optical depth of the hot corona and on the assumed law for the soft flux. The main result is the strong dependence of the polarization properties on the energy, and in particular the orthogonality between the UV/soft X-ray and the hard X-ray polarizations.

Key words: polarization – radiative transfer – galaxies: active – X-rays: stars.

1 INTRODUCTION

The origin of the X-ray emission in active galactic nuclei (AGN) is still an open issue. For many years, efforts have been devoted to the explanation of the 'universal' power-law spectrum ($\alpha \simeq 0.7$: Mushotzky 1984; Turner & Pounds 1989). Recently, *Ginga* observations have revealed that the X-ray spectra above 1 keV of a large fraction of Seyfert galaxies are more complex than was previously believed, resulting from the sum of several components (Pounds et al. 1990; Matsuoka et al. 1990; Piro, Yamauchi & Matsuoka 1990). In particular, added to a primary power law with $\alpha \simeq 0.9$–1, a fluorescent iron line and a high-energy bump, probably due to the reprocessing of the primary photons by cold matter (as predicted by Guilbert & Rees 1988 and Lightman & White 1988 and studied in detail by George & Fabian 1991 and Matt, Perola & Piro 1991), were discovered to be common, at least for low-luminosity objects (Nandra 1991; Williams et al. 1992). Moreover, there is increasing evidence for similar spectra in several Galactic X-ray binaries, in particular black hole candidates (Tanaka 1991; Ebisawa et al. 1992; Done et al. 1992). These observations, indicating that the primary spectrum is softer than was previously believed, have renewed interest in pair-production models, which naturally lead to the observed power-law spectral index (Zdziarski et al. 1990).

However, the observed spectra can also be explained in terms of unsaturated Comptonization of soft photons by hot, thermal electrons (e.g. Sunyaev & Titarchuk 1980). The natural source of the soft photons is the accretion disc, which is likely to be present around the central engine and is probably responsible, in AGN, for the ultraviolet (UV) bump (e.g. Malkan 1983), the soft X-ray excess (e.g. Arnaud et al. 1985) and the X-ray reprocessing (e.g. Matt et al. 1992). Recently, Haardt & Maraschi (1991, hereafter HM91) proposed a two-phase model in which hot, thermal electrons in an optically thin layer Comptonize the soft photons coming from an underlying colder, optically thick accretion disc. The two phases are coupled, in the sense that the balance of the power in the three main components, namely the blackbody and the X-ray reprocessed components from the thick phase and the power law from the thin phase, has been calculated in a self-consistent way. The resulting spectra are in agreement with the observations and are largely independent of the details of the model.

Besides the usual spectral and temporal information, polarization measurements can be very useful for distinguishing between different models and for constraining model parameters. In this paper we present detailed calculations of the expected polarization in the two-phase model mentioned above, and we show how such measurements are able to constrain the parameters of the system. The polarization properties have been calculated by using the method of solution of the radiative transfer equation for a pure scattering, plane-parallel atmosphere (Chandrasekhar 1960) involving separation of the different scattering orders, as described in Sunyaev & Titarchuk (1985). The polarization of the reflected radiation (Matt et al. 1989; Matt 1993) has also been taken into account.

In Section 2 a brief description of the two-phase model is presented, while in Section 3 the computational details are described. The results are reported in Section 4 and discussed in Section 5. In the near future, an X-ray polarimeter will fly on-board the Russian *Spectrum-X-Gamma* mission;

the observational perspectives are briefly discussed at the end of Section 5.

2 THE TWO-PHASE MODEL

In this paper we refer to the two-phase model proposed by HM91; further details and a more complete discussion are given by Haardt & Maraschi (1993). Here we briefly recall the main properties and results. We consider a picture in which X-rays are produced via inverse Compton emission in a hot tenuous corona embedding a colder disc. The energy distribution of the electrons in the corona is assumed to be Maxwellian. About half of the high-energy photons are effective in heating the underlying dense layers, while the electrons are cooled by the thermal radiation from these layers. In such a balanced situation, the electron temperature will adjust so as to maintain comparable luminosity in the soft and in the hard components of the emitted radiation.

The main parameter of the model is the fraction f of gravitational power dissipated in the hot corona. Excellent agreement with observed X-ray spectra of radio-quiet AGN is found when $f\sim 1$, i.e. the gravitational power is dissipated outside the disc. We note that the observed upper limit on the delay between variations in the optical and UV fluxes from some AGN (e.g. Courvoisier & Clavel 1991) seems to require that a large fraction of the power cannot be dissipated via viscosity in an accretion disc.

The energy balance equations described in HM91 determine the value of the Compton parameter y, which is found to be about 0.6. Therefore, the relation between the Thomson optical depth τ_0 and the electron temperature Θ (in units of the electron rest energy) in the hot phase is

$$(16\Theta^2+4\Theta)\,\tau_0\sim 0.6. \qquad (1)$$

The resulting high-energy spectra are largely independent of model details. The asymmetry in the soft flux produces an anisotropic inverse Compton emission (the importance of such an effect for the X-ray emission in AGN has been suggested, in a different picture, by Ghisellini et al. 1991 and by Rogers & Field 1991). The shape of the upward component is a power law with energy index $\simeq 0.9-1$, in agreement with the observed value for Seyfert galaxies (Nandra 1991).

3 METHOD OF COMPUTATION

The equation of radiative transfer for a pure scattering, axisymmetric and plane-parallel atmosphere can be written as

$$\mu\frac{\mathrm{d}\boldsymbol{I}(\tau,\mu)}{\mathrm{d}\tau}=\boldsymbol{I}(\tau,\mu)-\frac{3}{8}\int_{-1}^{+1}\mathbf{S}(\mu,\mu')\boldsymbol{I}(\tau,\mu')\,\mathrm{d}\mu'-\boldsymbol{F}(\tau,\mu) \qquad (2)$$

(e.g. Chandrasekhar 1960), where μ is the cosine of the angle between the direction of the photon and the axis of the layer, and τ is the optical depth along the vertical direction: $\tau=0$ at the upper bound and τ_0 at the lower bound (i.e. in our geometry, the boundary between the two phases). The intensity of the radiation field is $\boldsymbol{I}=(I_l, I_r)$, while $\boldsymbol{F}=(F_l, F_r)$ is the source function; l and r refer to the components in the meridian plane (defined by the direction of the photon and the normal to the layer) and perpendicular to it respectively. For symmetry reasons, these two components completely describe the radiation field. The total intensity I is the sum of I_l and I_r and the degree of polarization P is given by

$$P=\frac{I_r-I_l}{I_r+I_l}. \qquad (3)$$

By definition, the polarization is negative (positive) when the polarization vector lies in (perpendicular to) the meridian plane. $\mathbf{S}(\mu,\mu')$, the Rayleigh phase matrix, is given by

$$\mathbf{S}=\begin{pmatrix}2(1-\mu^2)(1-\mu'^2)+\mu^2\mu'^2 & \mu^2\\ \mu'^2 & 1\end{pmatrix} \qquad (4)$$

(equation [I.227] in Chandrasekhar 1960).

Following Sunyaev & Titarchuk (1985), we rewrite the intensity $\boldsymbol{I}$ as

$$\boldsymbol{I}=\sum_{k=0}^{\infty}\boldsymbol{I}^k, \qquad (5)$$

where $\boldsymbol{I}^k$ represents the intensity of the photons which have suffered k scatterings. The equation for $\boldsymbol{I}^k$ is then

$$\mu\frac{\mathrm{d}\boldsymbol{I}^k(\tau,\mu)}{\mathrm{d}\tau}=\boldsymbol{I}^k(\tau,\mu)-\frac{3}{8}\int_{-1}^{+1}\mathbf{S}(\mu,\mu')\boldsymbol{I}^{k-1}(\tau,\mu')\,\mathrm{d}\mu',\qquad k\geq 1. \qquad (6)$$

The solution, with the boundary condition

$$\boldsymbol{I}^k(0,-\mu)=\boldsymbol{I}^k(\tau_0,\mu)=0,\qquad 0\leq\mu\leq 1,\qquad k\geq 1, \qquad (7)$$

is

$$\boldsymbol{I}^k(\tau,\mu)=\frac{3}{8}\int_{\tau}^{\tau_0}\frac{1}{\mu}\exp\left(-\frac{\tau'-\tau}{\mu}\right)\int_{-1}^{+1}\mathbf{S}(\mu,\mu')\boldsymbol{I}^{k-1}(\tau',\mu')\,\mathrm{d}\mu'\,\mathrm{d}\tau',\qquad 0\leq\mu\leq 1,\qquad k\geq 1, \qquad (8)$$

$$\boldsymbol{I}^k(\tau,\mu)=\frac{3}{8}\int_{\tau}^{0}\frac{1}{\mu}\exp\left(-\frac{\tau'-\tau}{\mu}\right)\int_{-1}^{+1}\mathbf{S}(\mu,\mu')\boldsymbol{I}^{k-1}(\tau',\mu')\,\mathrm{d}\mu'\,\mathrm{d}\tau',\qquad -1\leq\mu\leq 0,\qquad k\geq 1. \qquad (9)$$

Strictly speaking, the above equations give the correct solution for the angular dependence of the intensity only in the Thomson regime, and for non-relativistic electrons. However, because a more general analytical treatment has not yet been developed, for the sake of simplicity we have used the described method over the full range of parameters.

The source function, i.e. the soft input flux emitted by the thick, colder phase, is given by

$$\boldsymbol{F}=\begin{cases}\boldsymbol{F}(\mu)\,\delta(\tau-\tau_0), & 0\leq\mu\leq 1;\\ 0, & -1\leq\mu\leq 0.\end{cases} \qquad (10)$$

We have used two different laws for the angular dependence of the soft input flux: a 'limb darkening' law (Chandrasekhar

1960) corresponding to a pure scattering, semi-infinite disc, and an isotropic intensity to model an absorption-dominated disc. In the first case, the soft radiation is polarized, with a positive (in the sense defined above) polarization degree between 0 ($\mu=1$) and 11.7 per cent ($\mu=0$); we have determined an analytical approximation for $F_l(\mu)$ and $F_r(\mu)$ by fitting the values tabulated in Chandrasekhar (1960, table XXIV):

$$F_l(\mu)=F_0\mu(0.1441+0.3559\mu);$$
$$F_r(\mu)=F_0\mu(0.1825+0.3176\mu). \qquad (11)$$

In the isotropic case, the radiation is unpolarized:

$$F_l(\mu)=F_r(\mu)=\frac{1}{2}F_0\mu. \qquad (12)$$

It must be noted that the observations seem to rule out the pure scattering disc. However, because the exact angular distribution of the intensity and the polarization of the disc thermal radiation is at present unknown, we adopt these two laws as two extreme examples; it seems plausible that the real situation is intermediate between these two cases. In both cases, the assumed spectral shape is a blackbody with a temperature $T_{\rm bb}$.

For a given energy and angle, the relative fraction $A^k(E,\mu)$ of the photons which have suffered k scatterings has been calculated as a function of τ_0 and of the soft flux parameters by using the analytical formulae described by Haardt (1993).

A fraction (which can exceed 50 per cent, see HM91) of the X-rays produced in the hot corona come back to the disc. These photons can be Compton-scattered by the cold matter into the line of sight and, adding to the primary radiation, modify the observed spectrum. This reflected radiation is polarized, with degree and angle of polarization which depend on the geometrical parameters of the system and on the polarization of the impinging photons (Matt 1993). We have taken into account the polarization, $P_r(\mu)$, of the reflected X-rays assuming that all the reflected photons are only once scattered, a good approximation up to a few tens of keV if the matter is neutral. In this approximation, P_r is independent of the energy. Possible further scatterings of these reflected photons in the hot corona have been neglected.

Finally, the net polarization as seen by the observer is given by

$$P(E,\mu)=\frac{N_{\rm cd}(E,\mu)\sum_k A^k(E,\mu)P^k(\mu)+N_{\rm cr}(E,\mu)P_r(\mu)}{N_{\rm cd}(E,\mu)+N_{\rm cr}(E,\mu)},$$
$$k\geq 0, \qquad (13)$$

where $P^k=(I_r^k-I_l^k)/(I_r^k+I_l^k)$. $N_{\rm cd}$ and $N_{\rm cr}$ are the energy distributions of the primary and reflected photons respectively; the ratio $N_{\rm cr}/N_{\rm cd}$ is a strong function of the energy, being negligible up to a few keV and reaching values of the order of unity (depending on the inclination angle) at a few tens of keV (e.g. Matt et al. 1991).

For simplicity, we have neglected the general relativistic effects (for discussions and results on the polarization of the radiation emitted near a black hole, see Pineault 1977; Connors, Piran & Stark 1980; Laor, Netzer & Piran 1990; Chen & Eardley 1991; Matt 1993).

4 RESULTS

As described in Section 2, the electron temperature and the optical depth in the hot phase are not independent. Therefore, the polarization properties depend on τ_0, the energy, the inclination angle, and the details of the soft radiation. In particular, the degree of polarization is a strong function of the number of scatterings, which increases with the photon energy, τ_0 and the inclination angle.

In Figs 1–6 we show the degree of polarization as a function of the energy, for different values of μ and τ_0. $T_{\rm bb}$ is assumed equal to 10 eV (Figs 1 and 2), 50 eV (Figs 3 and 4)

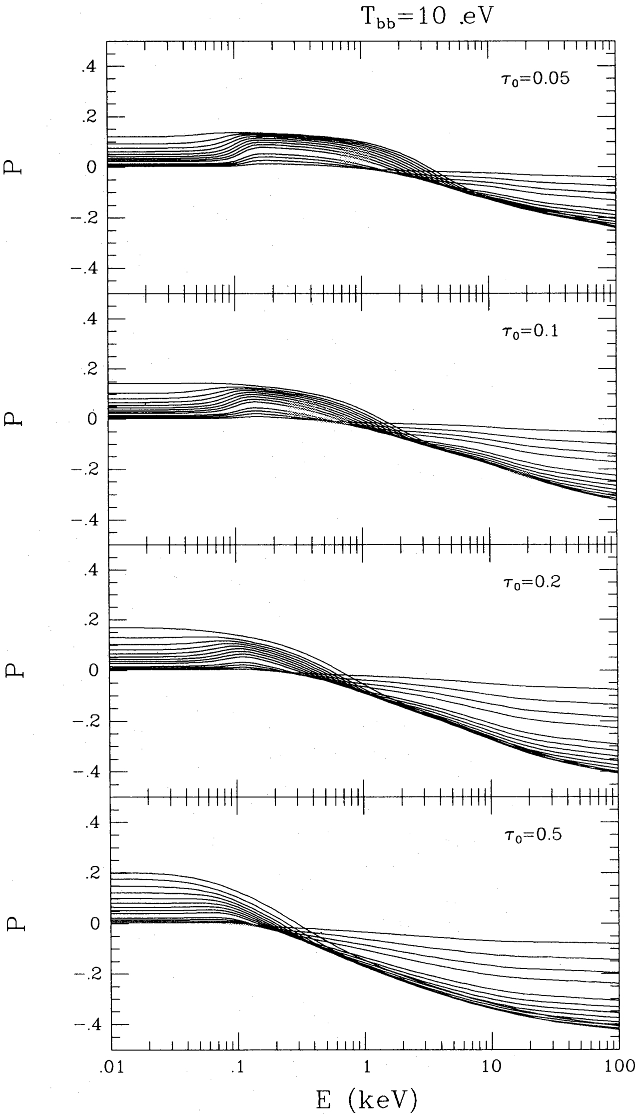

Figure 1. The degree of polarization as a function of the energy for four values of τ_0, and $T_{\rm bb}=10$ eV. The source function is the limb darkening law (Chandrasekhar 1960). The different curves refer to different values of μ, the cosine of the angle between the line of sight and the normal to the layer [$\mu=(2n-1)/29$, $n=1$, 14]. At the two extremes of the energy range shown, the absolute value of P decreases with μ.

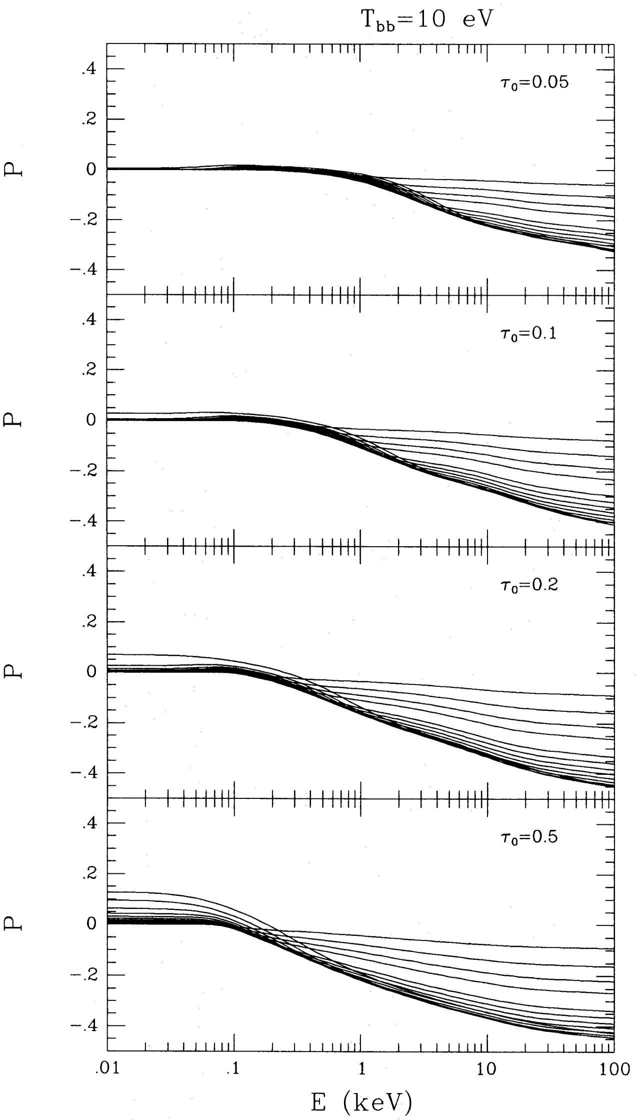

Figure 2. As Fig. 1, for $T_{bb} = 10$ eV and an isotropic source function.

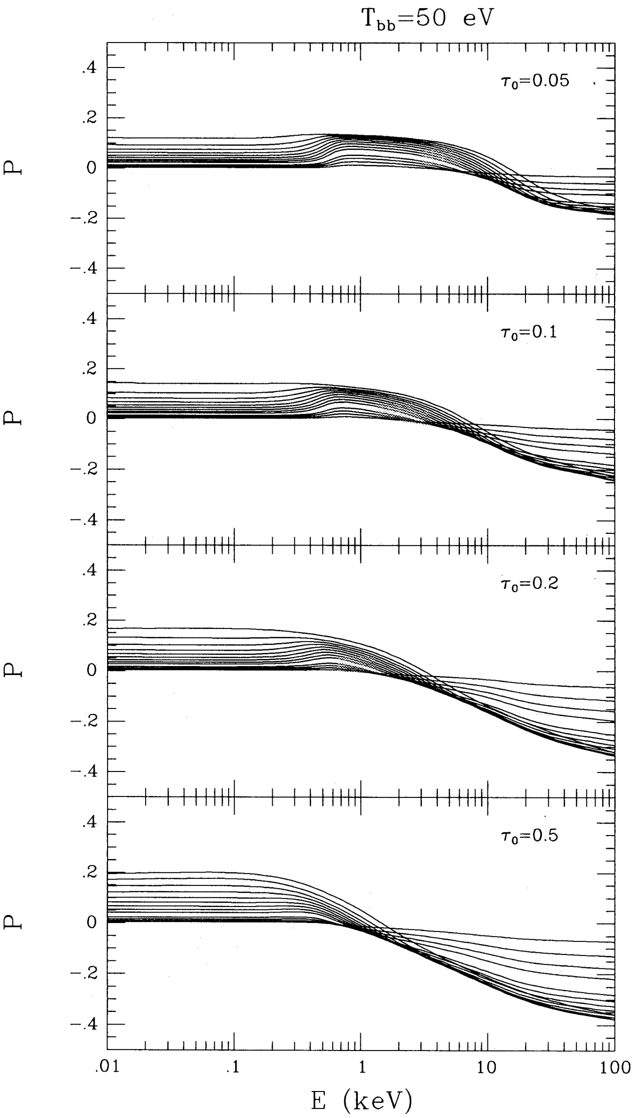

Figure 3. As Fig. 1, for $T_{bb} = 50$ eV and a limb darkening law for the source function.

or 1 keV (Figs 5 and 6). Figs 1, 3 and 5 refer to the limb darkening law source function, while Figs 2, 4 and 6 are obtained with the isotropic source function. Figs 1–4 are representative of an AGN, while temperatures of the order of 1 keV are likely to be present in the inner part of an accretion disc around a stellar-mass black hole. The different curves in each panel represent different values of μ, from 0.035 to 0.93 (at $\mu = 1$ the radiation is unpolarized). At the two extremes of the energy range, the absolute value of P decreases with μ.

The main results can be summarized as follows.

(i) The polarization is positive at low energies, and negative at high energies. The change occurs at 1–10 keV for AGN, and above 10 keV for a Galactic object, the exact value depending on μ, τ_0, T_{bb} and on the assumed law for the input soft photons. At low energies the polarization degree can reach values of about 20 per cent, while at high energies values as high as ~40 per cent are obtained. The sign of the polarization at a given energy reflects the mean number of scatterings suffered by the photons. The unscattered photons have positive polarization (when they are polarized), and so do the once-scattered photons, whereas photons scattered twice or more have a negative polarization, as well as the reflected radiation, which becomes important above ~10 keV. The exact value of the energy at which the polarization angle rotates depends on the various parameters, but the general result is that UV and soft X-rays are polarized orthogonally to the hard X-rays.

(ii) The degree of polarization decreases with μ (except around the energy at which the polarization angle changes). The maximum occurs in the edge-on case, while the radiation is unpolarized in the face-on case.

(iii) For an increase of τ_0, the degree of polarization generally increases. At low energies, this is due to the fact that the ratio between the (more polarized) once-scattered photons and the unscattered ones increases with the optical depth. At high energies, this is due to the fact that, at a given

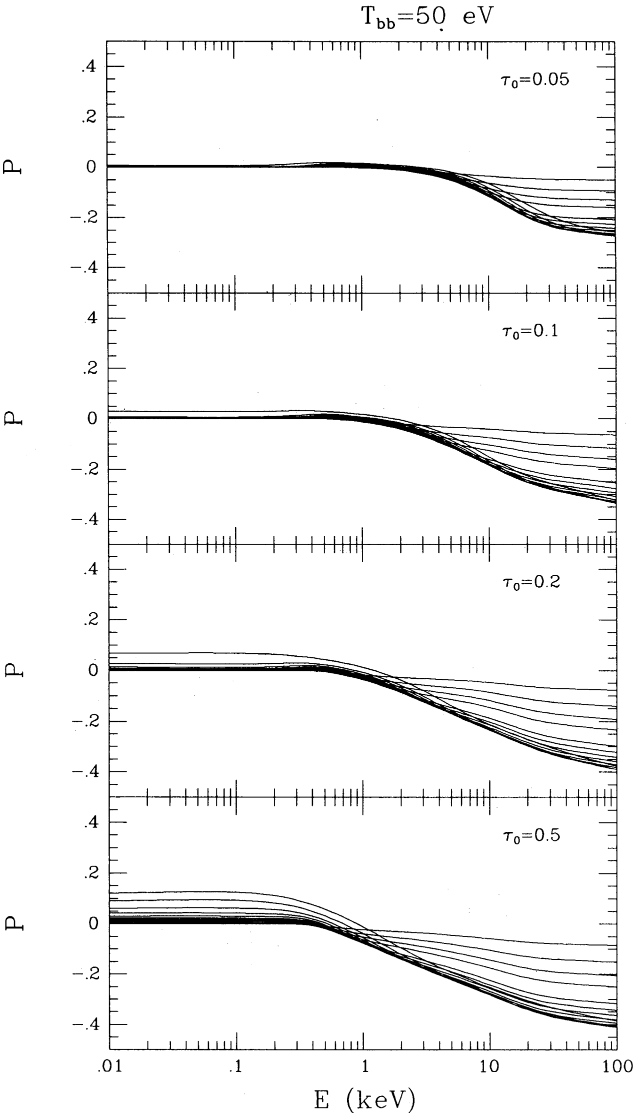

Figure 4. As Fig. 1, for $T_{\rm bb}=50$ eV and an isotropic source function.

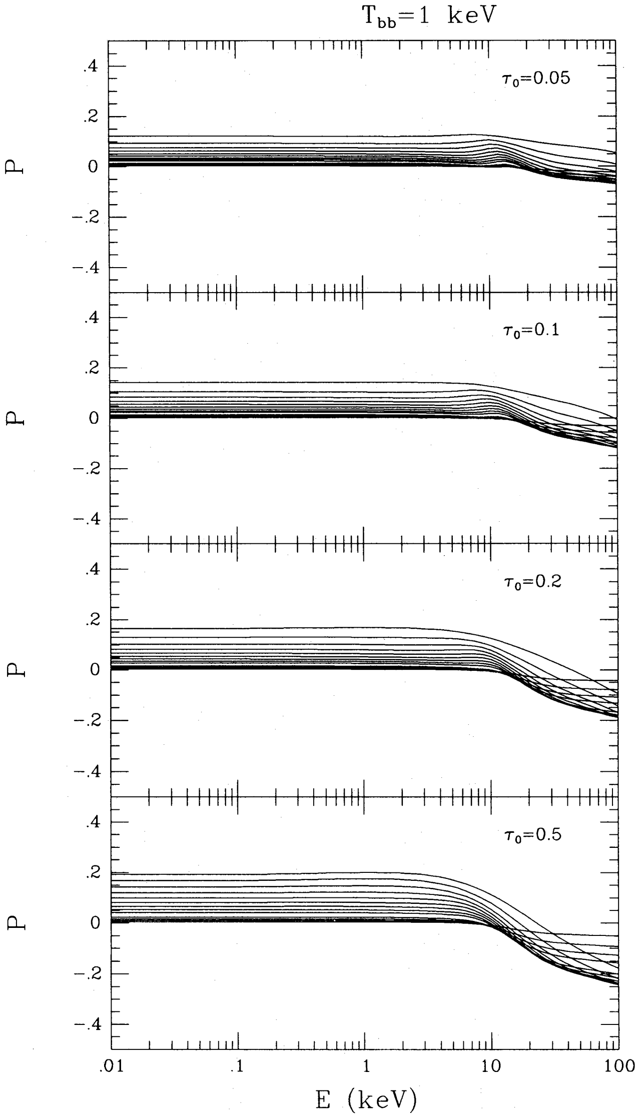

Figure 5. As Fig. 1, for $T_{\rm bb}=1$ keV and a limb darkening law for the source function.

energy, the number of scatterings suffered by the photons increases with τ_0; the degree of polarization increases with the number of scatterings, at least up to $k=15$–20, when it becomes practically independent of k.

(iv) For an increase of the blackbody temperature, the curves simply shift towards higher energies (apart from the contribution of the reflected radiation).

(v) The use of a limb darkening law instead of an isotropic law obviously leads to a much higher degree of polarization at low energies. Also at greater energies (above the change in the polarization angle), P is greater for the limb darkening law; the difference from the isotropic law diminishes for an increase of the energy and τ_0, because after a few scatterings the photons 'forget' the details of the source function.

5 CONCLUSIONS

We have calculated the polarization properties in the two-phase model proposed by HM91 to explain the X-ray emission of active galactic nuclei and Galactic black hole candidates. In this model, hot thermal electrons in an optically thin phase Comptonize the soft photons coming from an underlying, colder and optically thick phase to produce the X-rays. The model details, as well as discussion of the spectral results and comparison with the observations, can be found in HM91 and Haardt & Maraschi (1993).

We have studied the polarization as a function of the energy and of the inclination angle for several values of the parameters of the system, i.e. the optical depth τ_0 of the hot phase and the blackbody temperature of the soft radiation. A simple plane-parallel geometry has been adopted. We have considered two different laws for the angular dependence of the soft radiation: a limb darkening law (Chandrasekhar 1960) for a pure scattering, semi-infinite disc, and an isotropic law corresponding to an absorption-dominated disc. In the first case the input radiation is polarized (up to 11.7 per cent for an edge-on disc); in the second case it is unpolarized. It must be remarked that there is evidence of low optical polarization in Seyfert 1 galaxies and non-blazar QSOs

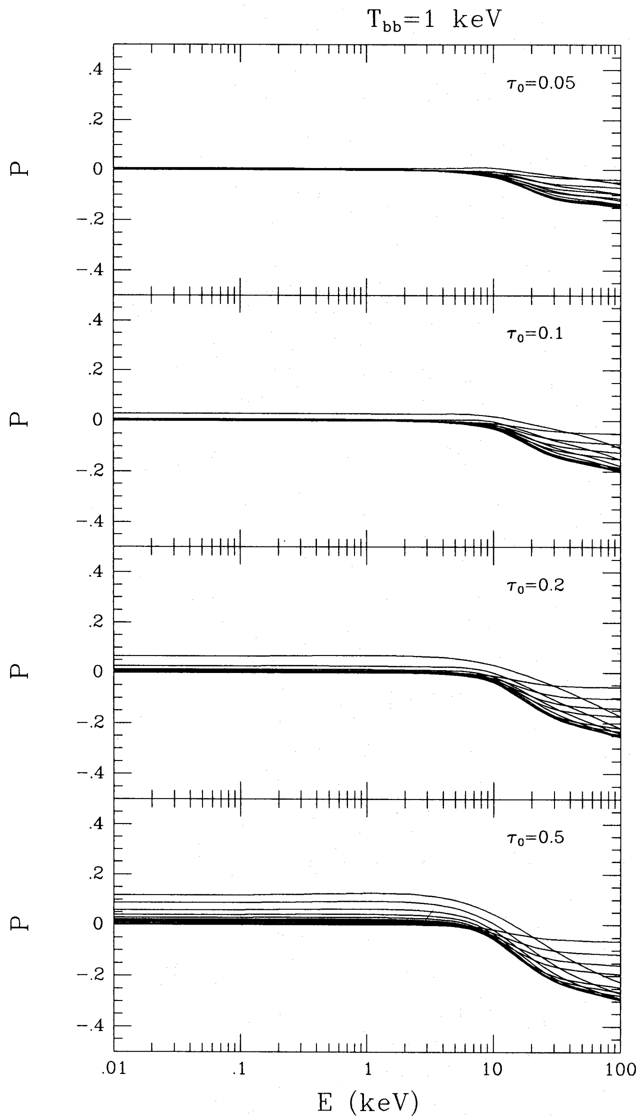

Figure 6. As Fig. 1, for $T_{bb} = 1$ keV and an isotropic source function.

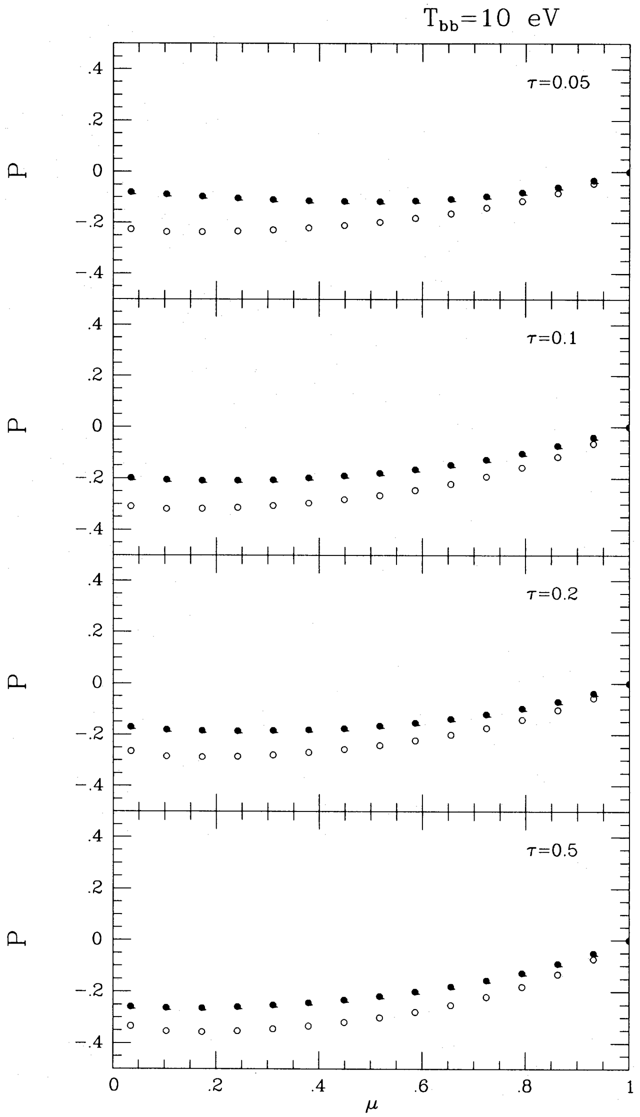

Figure 7. The degree of polarization versus μ, at 2.6 keV (filled circles) and averaged over the energy range 6–12 keV (open circles). $T_{bb} = 10$ eV and an isotropic law for the source function are assumed.

(e.g. Stockman, Moore & Angel 1984). Although other explanations have been invoked (Coleman & Shields 1990), this is probably due to the fact that the absorption opacity is not negligible, as pointed out by Laor et al. (1990). In fact, at least if the internal source function is not strongly increasing with the optical depth, a small deviation from a pure scattering atmosphere can dramatically reduce the degree of polarization (Loskutov & Sobolev 1979, 1981). The two assumed laws for the soft radiation must therefore be considered as two extreme examples. The true angular distribution plausibly lies between them, but it seems likely that it is closer to the unpolarized case.

For the sake of simplicity, we have assumed a blackbody law for the soft input radiation. Since the temperature changes along the radial coordinate of the disc, a multicolour spectrum could be more adequate. On the other hand, from X-ray variability considerations one can reasonably assume that the hot, X-ray emitting layer is confined above the inner part of the disc, and therefore the variation in the temperature is not very strong. In any case, if a temperature distribution is assumed, the results remain practically unchanged in the very low-energy limit (where the unscattered and once-scattered photons dominate) and in the very high-energy limit (where photons which have suffered a number of scatterings much greater than one dominate); the transition region between these two extremes will be broader and smoother.

The most relevant result is the strong dependence of the polarization on the energy. A signature of the model is the fact that the UV/soft X-ray polarization (which, however, is very small for the isotropic case and low optical depths) is positive, while the hard X-ray polarization is negative; i.e. the polarization angles in the two bands are orthogonal. After the rotation of the polarization angle (which for AGN occurs at 1–10 keV, and for Galactic X-ray binaries above 10 keV), the degree of polarization strongly increases with energy up to a few tens of keV.

The degree of polarization, as well as the energy at which it becomes negative, depends on τ, μ and on the temperature and the angular law of the soft photons; it can reach values as high as 30–40 per cent in the hard X-rays. In principle, once the characteristics of the thermal emission from the cold phase have been obtained by means of spectral measurements, polarization measurements can provide, besides a check of the model, very useful information on the optical depth of the hot phase (and therefore on the electron temperature) and on the inclination of the system.

In the near future, an X-ray polarimeter will fly aboard the Russian *Spectrum-X-Gamma* mission. SXRP (Stellar X-Ray Polarimeter: Kaaret et al. 1991) consists of two different polarimeters, working in parallel mode: a Bragg polarimeter, working at about 2.6 keV and (with lesser efficiency) at 5.2 keV, and a Thomson polarimeter working in the energy range 6–20 keV. In Fig. 7 we show the degree of polarization predicted by our model at 2.6 keV and in the band 6–12 keV, as a function of μ and for four values of τ_0 ($T_{\rm bb} = 10$ eV). SXRP will be able to search, in an observing time of about a day, for polarization of the order of one per cent in some black hole candidates, and of a few per cent in the brightest active galaxies (Kaaret et al. 1991; Massaro et al. 1993). Our model predicts, for the AGN, a degree of polarization of this order or more (if the system is sufficiently inclined) at 2.6 keV, and up to ~ 30 per cent in the 6–12 keV energy range. A possible detection of such high polarization, together with a greater degree of polarization in the 6–12 keV energy range than at 2.6 keV (see Fig. 7), will support Comptonization models.

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