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X-rays from hot subdwarfs

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Abstract

Thanks to the high sensitivity of the instruments on board the *XMM-Newton* and *Chandra* satellites, it has become possible to explore the properties of the X-ray emission from hot subdwarfs. The small but growing sample of hot subdwarfs detected in X-rays includes binary systems, in which the X-rays result from wind accretion onto a compact companion (white dwarf or neutron star), as well as isolated sdO stars in which X-rays are probably due to shock instabilities in the wind. X-ray observations of these low mass stars provide information which can be useful also for our understanding of the winds of more luminous and massive early-type stars and can lead to the discovery of particularly interesting binary systems.

Keywords: X-rays; Hot subdwarfs; Mass-loss; Binaries; White dwarfs; Neutron stars

1. Introduction

While soft X-ray emission from massive OB stars has been discovered more than thirty years ago (Seward et al., 1979; Harnden et al., 1979), only in recent years, thanks to the great sensitivity of the X-ray instrumentation carried by the *XMM-Newton* and *Chandra* satellites, it has become possible to reveal in the X-ray range also hot stars with much smaller masses and luminosities, such as the hot subdwarfs. These stars have high temperatures, corresponding to O and B spectral types, but luminosity values that place them below the main sequence in the HR diagram.

The B type subdwarfs (sdBs) have masses of $\sim$0.5 $M_{\odot}$, effective temperatures $20 < T_{\rm eff} < 40$ kK, and surface gravities $5 < \log g < 6$. They are interpreted as evolved low-mass stars that lost most of their hydrogen envelopes and are now in the He-core burning phase. Subdwarfs of O spectral type (sdOs) constitute a less homogeneous group compared to the sdBs. They show a large range of temperatures ($40 < T_{\rm eff} < 100$ kK) and surface gravities ($4 < \log g < 7$), and comprise both He-rich and He-poor stars.

X-ray emission associated with a hot subdwarf was seen for the first time in 1979 (see Section 3.1), but it took almost two decades to demonstrate that most of the observed X-rays actually originate from its compact companion star (Israel et al., 1997). Since then, little progress has been made in this field, until the developments of the last few years.

Extensive information on hot subdwarfs can be found in the excellent review by Heber (2009), which, however, does not cover their high-energy properties, having been written before most of the results described below were obtained. The aim of this paper is to review the X-ray properties of hot subdwarfs and discuss their relevance in the context of our understanding of mass-loss from hot stars. After a brief introduction on the X-ray emission from early-type stars[1] and on the current knowledge of mass-loss in hot

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[1] An exhaustive coverage of this topic is provided by the other articles of this Special Issue.

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subdwarfs (Section 2), we describe all the available X-ray observations of hot subdwarfs in Section 3. The interpretation of these observations, in particular their implications on the stellar wind properties and on the subdwarfs with compact companions, are discussed in Section 4.

2. Relevance of X-ray observations of hot subdwarfs

There are two main processes that can lead to the production of X-rays in hot subdwarf stars: wind emission and accretion onto a compact companion. In both cases, X-ray observations can give information on the star properties, although, strictly speaking, the latter process does not involve emission from the hot subdwarf itself. The detection of accretion-powered emission gives the possibility to discover the hot subdwarfs with white dwarf or neutron star companions, which are predicted from evolutionary calculations, but not easily identified with optical observations.

It is well known that early-type stars can generate X-rays if their stellar winds contain plasma sufficiently hot to emit in this energy range. In the following, we will call this process "intrinsic" X-ray emission. Extrapolating to lower luminosities the empirical relation between X-ray and bolometric luminosity observed in normal OB stars, $L_X/L_{BOL} = 10^{-7\pm1}$ (Pallavicini et al., 1981; Nazé, 2009), one can estimate the expected X-ray emission for hot subdwarfs. This leads to expected X-ray luminosities of the order of 10^{27-32} erg s^{-1} and 10^{26-29} erg s^{-1} for O and B type subdwarfs, respectively. It must be remembered, however, that the above average relation has a large scatter.

The second possibility is that X-rays are produced by accretion onto a compact companion star, which can be either a white dwarf (WD) or a neutron star (NS).[2] As a first approximation, the accretion rate can be estimated using the Bondi–Hoyle formalism,[3] according to which the accretion radius onto an object of mass M is given by $R_A = 2GM/(V_W^2 + V_{ORB}^2)$, where V_W is the wind velocity and V_{ORB} is the orbital velocity. The mass accretion rate $\dot{M}_A$ is related to the relative velocity $V_R = (V_W^2 + V_{ORB}^2)^{1/2}$ and to the wind density by $\dot{M}_A = \pi R_A^2 \rho V_R$. The wind density ρ at the position of the compact object can be estimated as $\dot{M}_{\rm W} = 4\pi a^2 \rho V_W$, where $\dot{M}_{\rm W}$ is the wind mass-loss rate from the subdwarf and a is the orbital separation. From these relations one obtains the accretion-powered luminosity of a star with mass M and radius R

$$L_X = \frac{GM}{R}\dot{M}_A = \frac{GM}{R}\left(\frac{R_A}{2a}\right)^2 \frac{V_R}{V_W}\dot{M}_{\rm W} \sim \frac{GM}{R}\left(\frac{R_A}{2a}\right)^2 \dot{M}_{\rm W} \quad (1)$$

Obviously, accretion onto a companion and intrinsic emission are not mutually exclusive, and both processes can occur in binary subdwarfs. In the lack of adequate X-ray data, it can be difficult to distinguish between the two possibilities, but, in both cases, the X-ray emission depends on the properties of the subdwarf's stellar wind. Therefore, X-ray observations provide a new diagnostic tool to investigate the poorly constrained mass-loss processes occurring in these stars.

2.1. X-ray emission in hot stars

Stars of O and B spectral type are sources of soft X-rays with luminosity up to a few 10^{33} erg s^{-1} and thermal spectra corresponding to plasma temperatures of a few million degrees. As well demonstrated, e.g., by the case of ζ Puppis (Hervé et al., 2013), high resolution X-ray spectra of the brightest OB stars can provide a wealth of information through the study of emission lines. However, for the majority of the early-type stars detected in X-rays, only low resolution spectra are available, which can be adequately fit using simple models of thermal plasma emission. For example, the spectra of a large sample of massive OB stars detected with *XMM-Newton* were described with either a single Mekal model with kT $\sim$ 0.2–1 keV, or with the sum of two or three Mekal models of different temperatures (Nazé, 2009). These data also showed evidence for additional[4] absorption, probably occurring in the stellar wind, in O stars but not in B stars.

Early-type stars are characterized by winds with typical mass-loss rates $\dot{M}_{\rm W}$ in the range 10^{-7}–10^{-5} M$_\odot$ yr^{-1} and terminal velocities of a few thousands km s^{-1}. It is believed that the observed X-rays are produced in these stellar winds, where the gas is shock-heated by instabilities (see, e.g., Owocki, 2013, for a review). The main properties of the winds in OB stars are explained in the context of the radiative line-driven wind theory (Castor et al., 1975; Kudritzki and Puls, 2000), according to which part of the radial momentum of the photons emitted from the star is transferred to the wind matter through line absorption and reemission. The theory predicts a dependence of $\dot{M}_{\rm W}$ on the star luminosity approximately given by $\dot{M}_{\rm W} \propto L^\alpha$, with $\alpha \sim$ 1.5–2. Since the photon absorption/emission process occurs mainly in the metals present in the wind, the mass-loss rate depends also on the metallicity Z, with $\dot{M}_{\rm W} \propto Z^b$ and $b \sim$ 0.6–0.7 (Vink et al., 2001). These theoretical scaling laws are generally in good agreement with the observational data. However, some discrepancies have been found in stars with low-density winds, which show mass-loss rates one or two orders of magnitude below the predicted values (Martins et al., 2005; Marcolino et al., 2009). Such discrepancies might be, at least partially, explained by the fact that the UV line diagnostics used in

[2] Also binaries composed of a hot subdwarf and a black hole can exist, but their formation is less frequent (Nelemans, 2010).

[3] We assume that the subdwarf radius is smaller than its Roche-lobe; this condition is verified in all the hot subdwarf binaries discussed below.

[4] With respect to the value expected for the interstellar medium along the line of sight.