Gamma-ray bursts, evolution of massive stars and star formation at high redshifts
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Ionization state of the interstellar medium in GRB host galaxies

E. O. Vasiliev*
Institute of Physics, Southern Federal University, Stachki Ave. 194, Rostov-on-Don, 344090, Russia

Abstract. Column densities of the highly-ionized species, C IV, N V and O VI, observed in the interstellar medium in the high redshift ($z > 2$) GRB host galaxies are analyzed using the non-equilibrium (time-dependent) photoionized model. It is found that the ionic ratios measured in the observations cannot be obtained with the photoionization model with super-solar metallicity. The possible ways to explain the observed ionic ratios are discussed.

Keywords : gamma rays: bursts - ISM: general

1. Introduction

Long-duration gamma-ray bursts (GRBs) are believed to be associated with star-forming regions of galaxies because their progenitors are likely to be massive stars (e.g., Woosley 1993). The lifetimes of massive stars are about several million years, therefore GRB afterglow observations could be a unique probe towards understanding the interstellar medium (ISM) within star forming region in the host galaxy. The circumburst medium in the high redshift ($z > 2$) GRB hosts could be studied by using absorption lines produced by highly-ionized species (e.g. OVI, CIV, SiIV and NV, whose ionization potentials are between 50-150 eV). Observations of ionized interstellar gas in galactic environments are probes of the hot gas ($T > 10^4$ K) and provide important constraints on physical processes (e.g. star formation, galactic winds) in the GRB host galaxies (Fox et al. 2008). In this paper, we analyze the high-ionic states observed in the GRB hosts using the non-equilibrium photo-ionized model.

*email: eugstar@mail.ru

2. Ionization states: equilibrium or non-equilibrium

Calculations for the ionic composition and cooling rates of astrophysical plasma in the collisional ionization equilibrium (CIE) were performed by many authors (House 1964; Raymond et al. 1976; Shull & van Steenberg 1982; Gaetz & Salpeter 1983; Böhringer & Hensler 1989; Sutherland & Dopita 1993; Bryans et al. 2006). However, calculations of the time-dependent ionization of metals and associated radiative cooling showed significant deviations from the CIE states (Kafatos 1973; Shapiro & Moore 1976; Schmutzler & Tscharnuter 1993; Sutherland & Dopita 1993; Gnat & Sternberg 2007). Under certain conditions, ionizing radiation can be important for the ionization states and radiative losses of the ambient gases. The presence of UV radiation could significantly over-ionize the ionization states and consequently, strongly suppress the cooling rates of a gas (Efstathiou 1992; Wiersma et al. 2009; Vasiliev 2011).

It is to be noted that both equilibrium and time-dependent collisional ionic composition have no dependence on the gas density, because all these processes are two-body. On the other hand, the ionic composition in the photo-ionization case strongly depends on gas density. Moreover, the ionizing radiation forces the ionic composition of gases to settle on to equilibrium. In low density gases, the ionic composition in the time-dependent photo-ionization case is expected to differ strongly from that both in collisional equilibrium and time-dependent cases, but it tends to the ionic fractions in the case of photo-equilibrium. In high density gases, we expect that the time-dependent photo-ionization ionic composition tends to be time-dependent collisional one, whereas the photo-equilibrium ionic fractions should be close to those in the case of CIE. The non-equilibrium ionic composition of photo-ionized gas differs strongly from that in the photo-equilibrium due to the over-ionization of ionic states in the former case. In addition, the ionic composition strongly depends on metallicity. For low metallicity the difference between time-dependent and equilibrium ionic fractions is expected to be small, but it increases with metallicity. Due to nonlinear dependence of ionic fractions on temperature, metallicity, and density (Vasiliev 2011) we consider the more complex, but more adequate non-equilibrium (time-dependent) photo-ionization model.

In our model, the thermal and ionization evolution of a gas exposed to external ionizing radiation is studied (more detailed description can be found in Vasiliev 2011). A gas parcel is assumed to be optically thin for the ionizing radiation. We consider the time-dependent equations for all ionization states of H, He, C, N, O, Ne, Mg, Si and Fe, including all relevant atomic processes: photo-ionization (the cross sections are adopted from Verner et al. (1996); Verner & Yakovlev (1995); Auger effect (probabilities taken from Kaastra & Mewe (1993)); collisional ionization (Voronov 1997); radiative and dielectronic recombination (Vasiliev 2011, see full list of references in) as well as charge transfer in collisions with H and He atoms and ions (Arnaud & Rothenflug 1985; Kingdon & Ferland 1996). This system of time-dependent ionization state equations should be complemented by the temperature equation, which accounts for all relevant cooling and heating processes. Here we assume that a gas parcel cools isochronically. The total cooling and heating rates are calculated using the photo-ionization code CLOUDY (ver. 08.00, Ferland et al. 1998). For the solar metallicity case, we adopt the abundances reported by Asplund et al. (2005), except Ne for which the enhanced abundance is adopted (Drake & Testa 2005). In all our calculations we assume the helium mass fraction to be $Y_{\rm He} = 0.24$. We solve a set of 96 coupled equations (95 for all ionization states of the elements and one for temperature) using a VODE solver (Brown et al. 1989). A shape of ionizing background spectrum used in the calculations can have an arbitrary form (e.g. black body, power-law and extra-galactic (Haardt & Madau 2001) backgrounds). We tested our code and calculated the CIE abundances and found a good coincidence between the results of our code and the original results by Mazzotta et al. (1998) as well as the standard CIE test of the CLOUDY code.

3. Ionic ratios in the GRB hosts

The ratio of column densities of ion i of element m and ion j of element n is

$$\frac{N_i^m}{N_j^n} = \frac{A_m}{A_n}\frac{x_i(T)}{x_j(T)}, \tag{1}$$

where A_m, A_n are the abundances of elements m and n (relative to H), x_i, x_j are the fractions of corresponding ionization states. We consider the ratios $N_{\rm CIV}/N_{\rm OVI}$ and $N_{\rm NV}/N_{\rm OVI}$ observed in GRB host absorbers (see their Table 9 of Fox et al. 2008) data. Fig. 1 shows these ratios for power-law spectrum with the index $\alpha = 1.7$ and two fluxes $J_{21} = 0.1$ and 0.01 in photo-equilibrium and photo-non-equilibrium. The "cooling tracks" are the gray diagrams, where the gray gradation corresponds to gas temperature. One can see that such tracks obtained for a Lagrangian parcel of gas cannot explain the observational points both in photo-equilibrium and photo-non-equilibrium models. For super-solar metallicity the tracks shift closer to the data, but it is difficult to fit the data even for metallicity $Z = 10\,Z_\odot$.

Certainly, gaseous flows in the GRB hosts have a complex turbulent structure and the simple description of a Lagrangian element cannot reflect the ionization states of such a structure correctly. Moreover, various gaseous layers having different ionic composition may deposit into the total column density of an ion measured in the observations along the line of sight. This might imply to a higher value of the measured CIV column density which may correspond to a shocked gas layer with lower temperature, whereas the NV and OVI absorption forms in a layer with higher temperature. However, both layers have small velocity gradients along the line of sight and consequently, they could be associated with the same absorption line. Such a picture could take place, when an expanding shell is crossed by the line of sight close to a tangent. The theoretical estimates from conductive interfaces are shown by the dashed region (CIs Borkowski et al. 1990) in Fig. 1. However, the same ionic ratios could also be

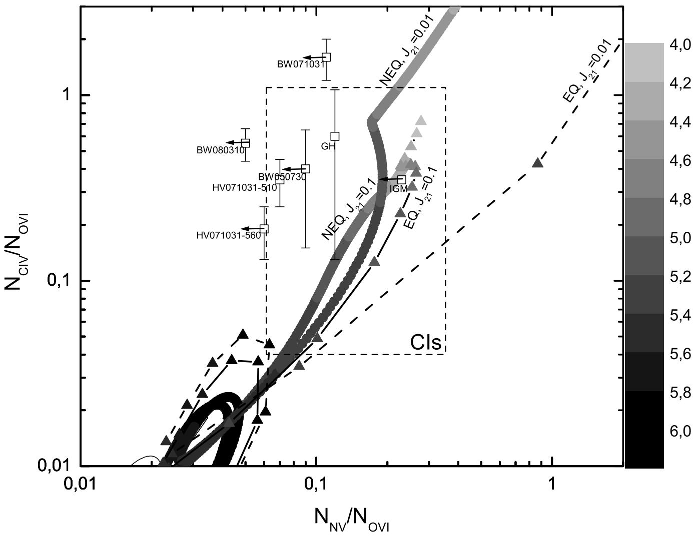

Figure 1. The dependence $N_{\rm CIV}/N_{\rm OVI}$ versus $N_{\rm NV}/N_{\rm OVI}$ in the photo-non-equilibrium model for cooling gas with $n = 10^{-4}$ cm^{-3} and $Z = Z_\odot$ exposed to the power-law ionizing radiation spectrum with the index $\alpha = 1.7$ and two fluxes $J_{21} = 0.01$ and 0.1 (the corresponding labels are shown). The same dependence in the photo-equilibrium are by triangles connected by solid line for $J_{21} = 0.1$ and by dashed line for $J_{21} = 0.01$. Gas temperature is indicated by gray scale along the trajectories: from hot (black) to cold (light gray) gas. The data points show the ionic ratios observed in GRB host absorbers (see Table 9 of Fox et al. 2008). The ratios for the Galactic halo and intergalactic medium are marked by "GH" and "IGM" labels, correspondingly. Also, for instance, the theoretical estimates from conductive interfaces are shown by the dashed region (CIs Borkowski et al. 1990).

obtained due to hydrodynamic instabilities in the process of mixing layers (de Avillez & Breitschwerdt 2009; Slavin et al. 1993).

Thus, we have concluded that the ionic ratios measured in the GRB host absorbers cannot be obtained with the photoionization models with metallicity $Z \leq 10Z_\odot$, and such ionic ratios could also be explained in turbulent mixing models.

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References

Arnaud M., Rothenflug R., 1985, A&AS, 60, 425
Asplund M., Grevesse N., Sauval A. J., 2005, in Barnes T. G. III, Bash F. N., eds, ASP Conf. Ser. 336, Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis (San Francisco: ASP), 25
Borkowski K. J., Balbus S. A., Fristrom C. C., 1990, ApJ, 355, 501
Böhringer H., Hensler G., 1989, A&A, 215, 147
Brown P. N., Byrne G. D., Hindmarsh A. C., 1989, SIAM J. Sci. Stat. Comput., 10, 1038
Bryans P., Badnell N. R., Gorczyca T. W., et al., 2006, ApJS, 167, 343
de Avillez M. A., Breitschwerdt D., 2009, ApJL, 697, 158
Drake J. J., Testa P., 2005, Nature, 436, 525
Efstathiou G., 1992, MNRAS, 256, 43
Ferland G. J., Korista K. T., Verner D. A., et al., 1998, PASP, 110, 761
Fox A. J., Ledoux C., Vreeswijk P. M., et al., 2008, A&A, 491, 189
Gaetz T. J., Salpeter E. E., 1983, ApJS, 52, 155
Gnat O., Sternberg A., 2007, ApJS, 168, 213
Haardt F., Madau P., 2001, in Neumann D. M., Tran J. T. V., eds, Clusters of Galaxies and the High Redshift Universe Observed in X-rays, astro-ph/0106018
House L. L., 1964, ApJS, 8, 307
Kaastra J.S., Mewe R., 1993, A&AS, 97, 443
Kafatos M., 1973, ApJ, 182, 433
Kingdon J. B., Ferland G. J., 1996, ApJS, 106, 205
Mazzotta P., Mazzitelli G., Colafrancesco S., et al., 1998, A&AS, 133, 403
Raymond J. C., Cox D. P., Smith B. W. 1976, ApJ, 204, 290
Schmutzler T., Tscharnuter W. M., 1993, A&A, 273, 318
Shapiro P. R., Moore R. T., 1976, ApJ, 207, 460
Shull J. M., van Steenberg M., 1982, ApJS, 48, 95
Slavin J. D., Shull J. M., Begelman M. C., 1993, ApJ, 407, 83
Sutherland R. S., Dopita M. A., 1993, ApJS, 88, 253
Vasiliev E. O., 2011, MNRAS 414, 3145
Verner D. A., Yakovlev D.G., 1995, A&AS, 109, 125
Verner D. A., Ferland G. J., Korista K. T., et al., 1996, ApJ, 465, 487
Voronov G. S., 1997, At. Data Nucl. Data Tables, 65, 1
Wiersma R., Schaye J., Smith B. D., 2009, MNRAS, 393, 99
Woosley, S. E. 1993, ApJ, 405, 273