Interaction of the gamma-ray burst with the interstellar gas of the parent galaxy: observational signatures

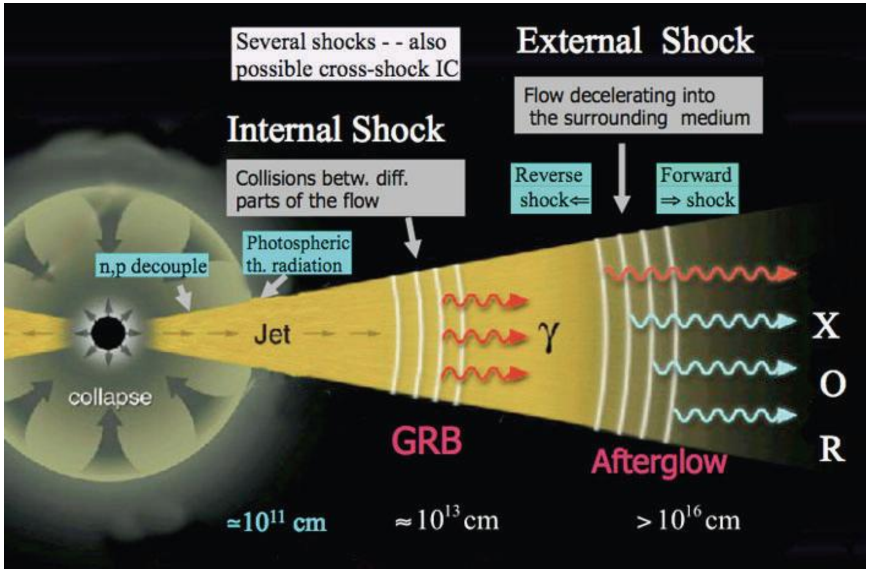
Nesterenok A.V.
Ioffe Institute, Saint Petersburg

Introduction

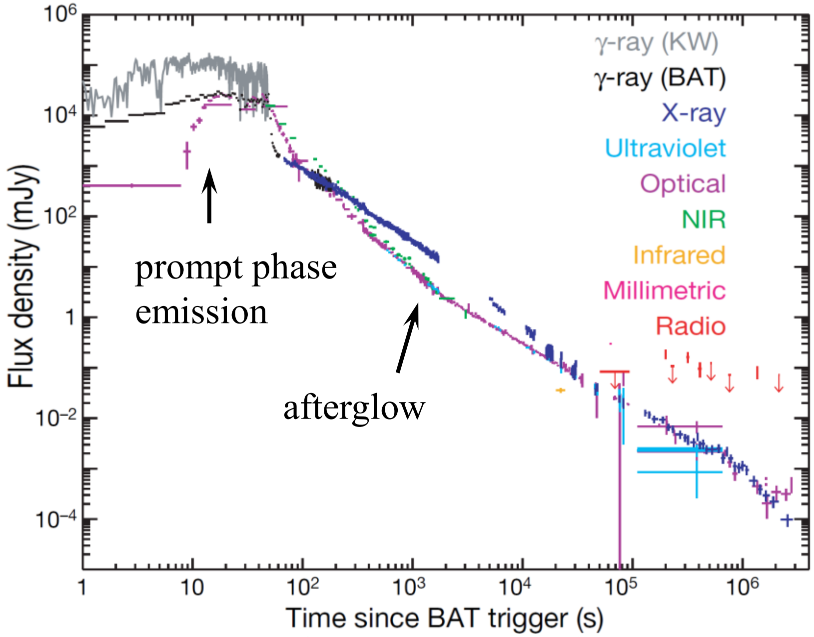
Gamma-ray bursts (GRBs) are extremely energetic events of the liberation of an enormous amount of ionizing radiation within several tens of seconds. The compact “central engine” formed by the collapse of a massive star or the merger of two compact stars launches a relativistic plasma jet:

- The energy dissipation in the jet produces the emission of the relatively short **prompt phase** that lies in the X-ray and gamma-ray wavelength ranges.
- The jet interacts with the external medium; the forward and reverse shocks are formed. **Optical flash** (reverse shock emission) and an **afterglow** (forward shock emission) are produced by the synchrotron mechanism.

Here, we consider **long-duration gamma-ray bursts** that are produced during the collapse of massive stars.

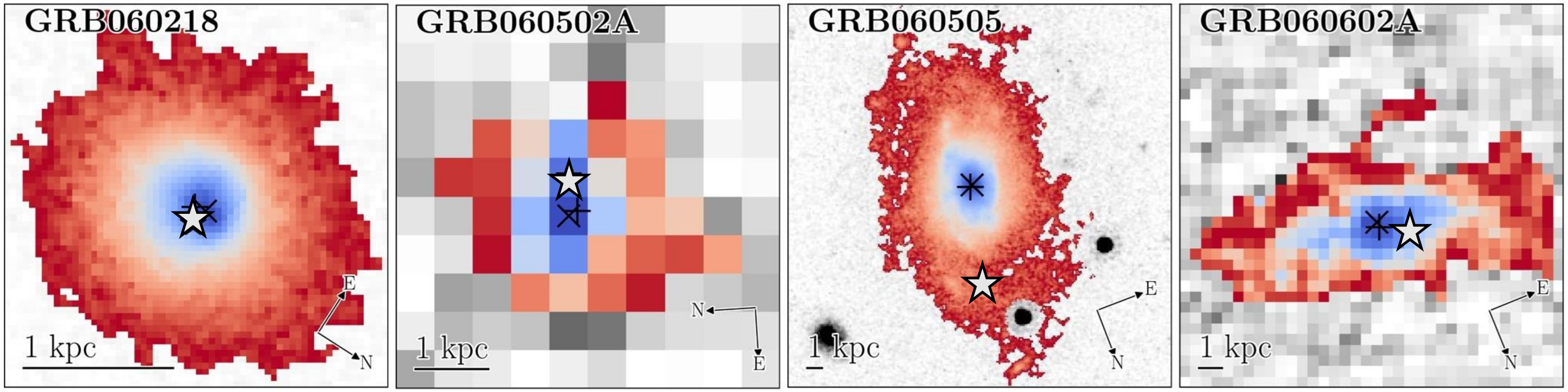


(Peer, 2015)



(Racusin et al. 2008; GRB 080319B)

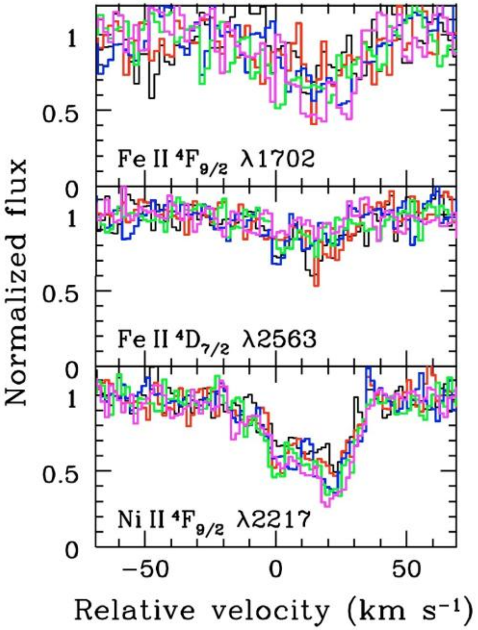
The results of *Hubble Space Telescope* survey of the host galaxies of long-duration gamma-ray bursts (Lyman et al. 2017):



- The hosts of long gamma-ray bursts are predominantly young and star-forming galaxies, consistent with the hypothesis of massive star progenitors.
- Long gamma-ray bursts are strongly biased towards the brighter regions in their host light distributions.
- The distribution of gamma-ray bursts is statistically consistent with the distribution of stripped-enveloped subtypes of core-collapse supernovae (type Ib/c and Ic-BL).

The signatures of interaction of the gamma-ray burst radiation with the interstellar gas

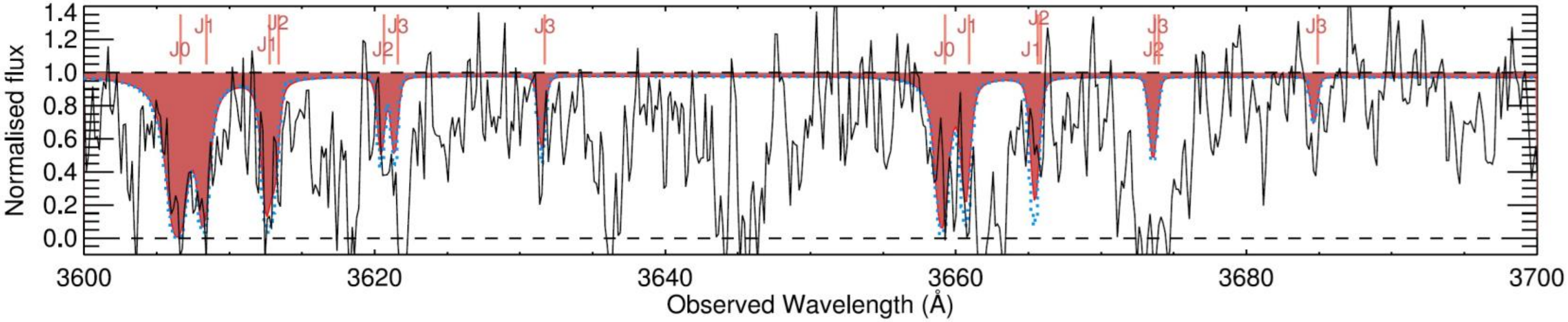
Afterglow spectra of GRB 060418 obtained with VLT/UVES (Vreeswijk et al. 2007, 2011).



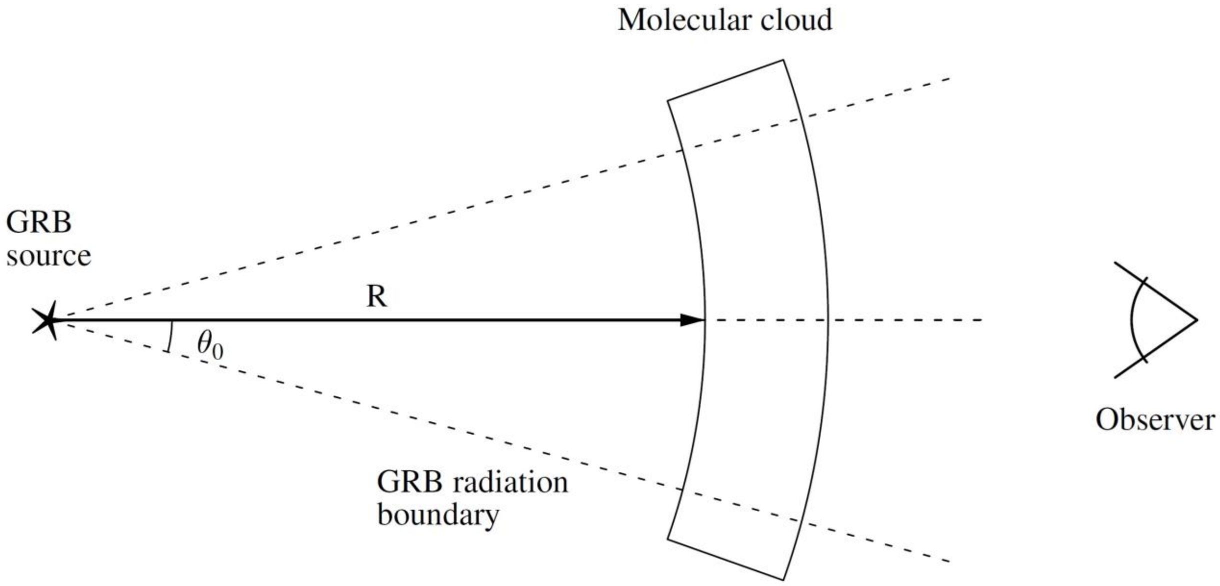
- The afterglow energy spectrum with a set of absorption lines of metal ions, hydrogen atoms and molecules contains information about the interstellar medium of the galaxy

- For some gamma-ray bursts, there is an evidence for time variability of metal ion lines. Based on the UV pumping model, the distance between gamma-ray burst source and absorbing gas may be estimated.

Afterglow spectra of GRB 121024A, H_2 absorption in the Lyman–Werner bands, X-shooter spectrograph on VLT (Friis et al., 2015)



Model of the gamma-ray burst and molecular cloud



- The composition of the gas is: H_2, H, He, dust ($MgFeSiO_4$), metal ions in the gas phase (C, N, O, Ne, Mg, Si, S, Fe). At the beginning of the simulations, the hydrogen is molecular, ortho-to-para-H_2 ratio is equal 0.1 (some arbitrary small value), all species are neutral.

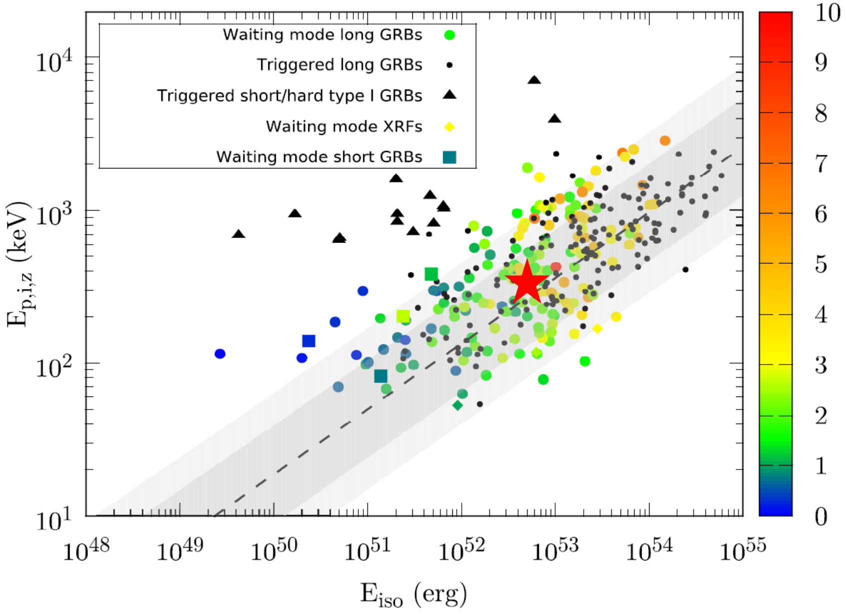
- The goal is to study the excitation of H_2 by UV emission of the gamma-ray burst, and to estimate the luminosity of infrared ro-vibrational transitions of H_2.

The Intensity of GRB Radiation

i). **The prompt emission** is characterized by two main parameters: the total isotropic-equivalent energy $E_{\gamma,iso}$ and the peak energy E_{peak} of the energy spectrum νF_ν in the rest frame (Band et al., 1993). In our model we chose:

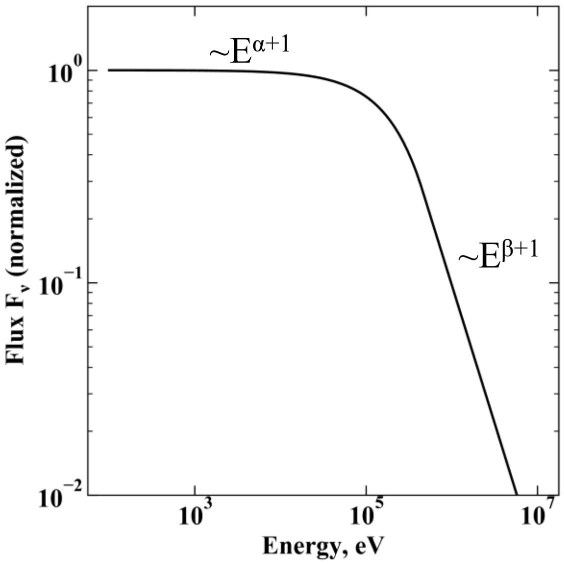
$$E_{\gamma,iso} = 5\times10^{52}\ \mathrm{erg}, \quad E_{peak} = 350\ \mathrm{keV}$$

The correlation between the parameters $E_{\gamma,iso}$ and E_{peak} – Amati relation:

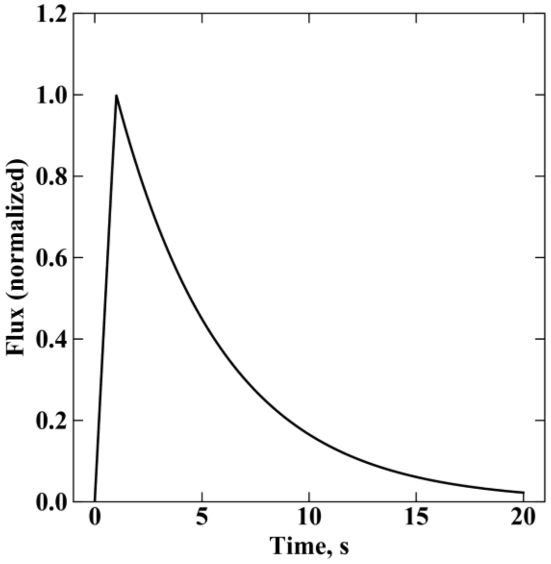


Konus gamma-ray spectrometer data for 338 gamma-ray bursts (Tsvetkova, 2021)

The spectral flux density of the emission, $\alpha = -1$, $\beta = -2.3$ (Kaneko et al. 2006):



Spectrum evolution with time:



ii). **Afterglow**

The afterglow is the forward shock emission. Energy spectrum was simulated using the code **afterglowpy** (Ryan et al., 2020). The observer is on the jet axis.

Parameters of the gamma-ray burst afterglow:

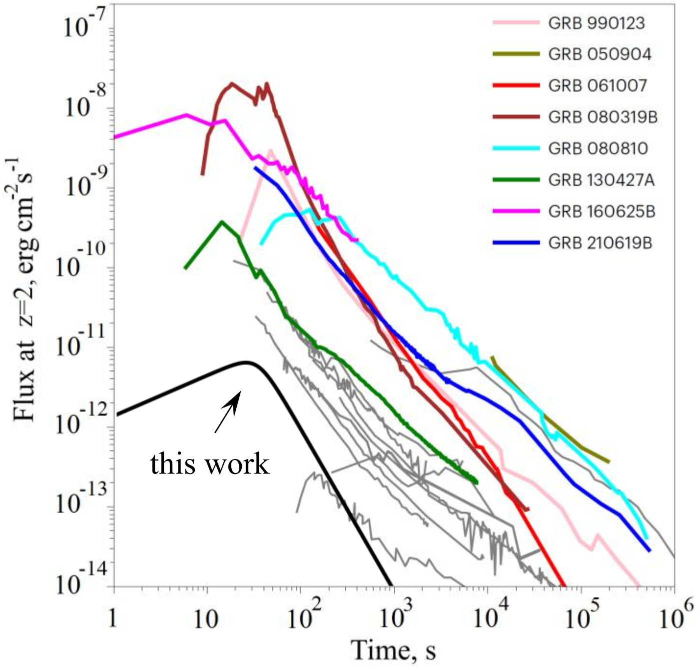
Kinetic energy of the jet, E_K	2.5×10^{53} erg	Zhang et al. (2007); Beniamini et al. (2016)
Fraction of energy in the magnetic field, ε_B	10^{-4}	Santana et al. (2014); Barniol Duran (2014)
Fraction of energy in the electrons, ε_e	0.1	Nava et al. (2014); Beniamini, van der Horst (2017)
Electron energy distribution index, p	2.3	Curran et al. (2010)
Jet opening angle, θ_j	0.1 rad	Ryan et al. (2015); Goldstein et al. (2016)
Density of the medium, n_0	1 cm^{-3}	Panaitescu, Kumar (2002); Schulze et al. (2011)

The ratio of the prompt emission energy and all energy of the jet:
$\eta = E_{\gamma,iso}/(E_{\gamma,iso} + E_K) \approx 0.2$.

iii). **Opticla flash**

The optical flash is observed simultaneously or immediately after the completion of the gamma-ray burst prompt emission. One of the explanations – the synchrotron radiation of the reverse shock.

Optical flash for some gamma-ray bursts (Oganesyan et al. 2023):



Evolution with time (Nakar, Piran, 2004, 2005):

$$F^r_{\nu,\mathrm{opt}}(t) = F^r_0\left[\frac{1}{2}\left(\frac{t}{t_0}\right)^{-s\alpha_1}+\frac{1}{2}\left(\frac{t}{t_0}\right)^{-s\alpha_2}\right]^{-(1/s)}$$

$\alpha_1 = 0.5$, $\alpha_2 = 2$, $s = 2$, $t_0 = 10$ s.

Maximal flux F^r_0:

$$F^r_0 = 0.1\ \mathrm{mJy}(1+z)^{-(4+p)/8}1.5^{2.5-p}\left[\frac{3(p-2)}{p-1}\right]^{p-1}$$

$$\times\ \epsilon_{e-1}^{p-1}\epsilon_{B-2}^{(p+1)/4}n^{(p+2)/8}E_{52}^{1+p/8}t_{0,2}^{-3p/8}D_{28}^{-2}A^r_{F,0}(\xi),$$

$$A^r_{F,0}(\xi) \approx 180\xi^{0.65}(6\times 10^{-4}\xi^{-2.6})^{(p-1)/2}.$$

The chosen parameters are:
$p = 2.3$; $\varepsilon_B = 10^{-4}$; $\varepsilon_e = 0.1$; $E_K = 3\times10^{53}$ erg; $\xi = 0.1$;

Interaction of the gamma-ray burst radiation with the gas-dust cloud

i) photoionisation and photodissociation of atoms and molecules

- **H_2 photoionisation** (Yan et al. 1998; 2000)

  $H_2 + h\nu \rightarrow H_2^+ + e^-$
- **H_2 dissociative photoionisation** (Chung et al. 1993)

  $H_2 + h\nu \rightarrow H + H^+ + e^-$
- **Photoionisation of H, He, and metal ions** (Verner, Yakovlev 1995; Verner et al. 1996)

  $X^{+a} + h\nu \rightarrow X^{+a+1} + e^-$
- **Photoionisation and photodissociation of H_2^+** (von Busch, Dunn 1972; Arkhipov et al. 2018)

  $H_2^+ + h\nu \rightarrow H^+ + H^+ + e^-$

  $H_2^+ + h\nu \rightarrow H + H^+ + e^-$
- **Compton ionisation**

  $H_2 + h\nu \rightarrow H_2^+ + e^- + h\nu$
- **H_2 photodissociation through absorption in Lyman and Werner bands** (Solomon process):

  $H_2 + h\nu \rightarrow H_2^* \rightarrow H + H$

  and direct photodissociation (Gay et al. 2012):

  $H_2 + h\nu \rightarrow H + H$

ii) dust absorption and dust particle evaporation

- Dust absorption in cloud layer with width ΔR:

$$\Delta\tau_{\mathrm{dust},j} = \pi r_{\mathrm{d}}^2 \left[Q_{\mathrm{abs}}(r_{\mathrm{d}},\nu) + Q_{\mathrm{sca}}(r_{\mathrm{d}},\nu)\right] n_{\mathrm{d}} \Delta R$$

Q_{abs}, Q_{sca} – absorption and scattering cross sections (normalized by geometric cross section)

- Dust particle evaporation (Waxman, Draine, 2000)

$$\frac{dr_{\mathrm{d}}}{dt} = -\left(\frac{m_{\mathrm{d}}}{\rho_{\mathrm{d}}}\right)^{1/3} \nu_0 \exp\left(-\frac{B}{k_{\mathrm{B}}T_{\mathrm{d}}}\right)$$

$B/k_B = 7\times10^4$ K, m_d – is the mean atomic mass of the dust material average; ρ – density of dust material; $\nu_0 = 10^{15}$ s^{-1}

- Equation for the balance of the dust grain heating and cooling rates:

$$C_{\mathrm{d}}\frac{dT_{\mathrm{d}}}{dt} = G_{\mathrm{GRB}} + G_{\mathrm{rad}} + G_{\mathrm{vap}}$$

cooling due to evaporation:

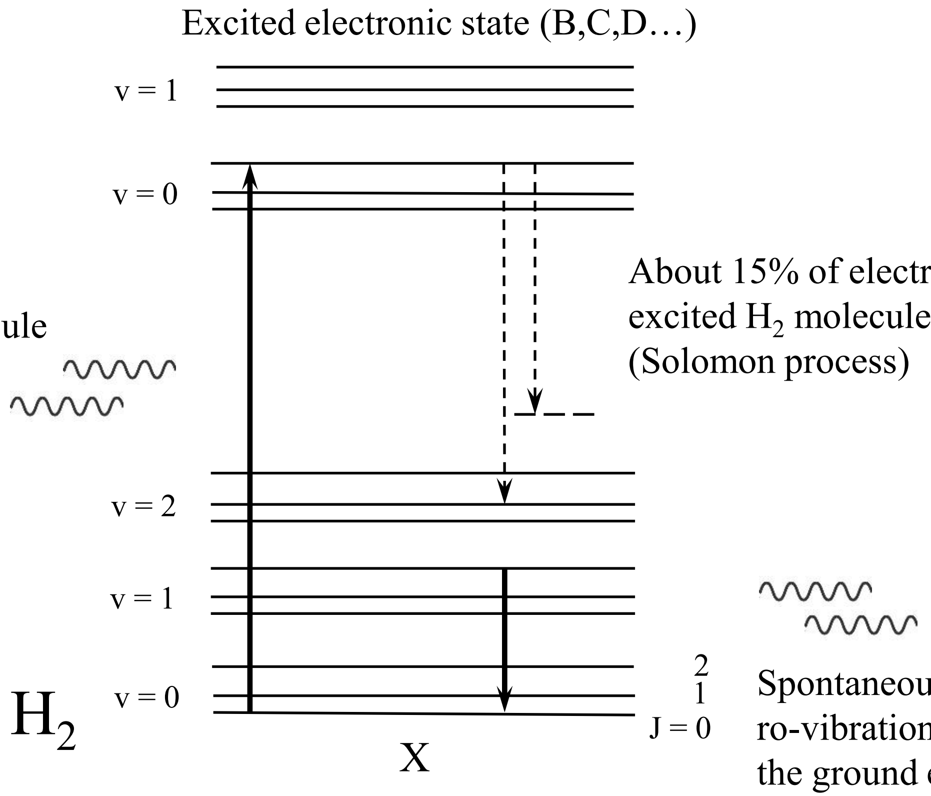
$$G_{\mathrm{vap}} = -4\pi r_{\mathrm{d}}^2 \frac{dr_{\mathrm{d}}}{dt}\frac{B\rho_{\mathrm{d}}}{m_{\mathrm{d}}}$$

heating by the GRB radiation

cooling through dust intrinsic radiation

The heat capacity of the dust grains C_d is equal to $3k_BN$ (Dulong–Petit law), where N is the number of atoms in grain (Draine, Li, 2001). This mechanism of dust evaporation leads to the destruction of dust particles at distances R ≤ 10 pc (depending on GRB parameters).

iii) H_2 excitation to excited electronic states by UV radiation of gamma-ray burst (by optical flash and afterglow)



UV emission of gamma-ray burst excites a transition to electronic states of H_2 molecule

About 15% of electronically excited H_2 molecules dissociate (Solomon process)

Spontaneous transitions between ro-vibrationally excited levels of the ground electronic state.

- The energies of ro-vibrational levels of excited electronic states B, C, B′, D, the Einstein coefficients for transitions connecting excited electronic states and the ground state are taken from data files of the CLOUDY code (Abgrall et al, 2000; Ferland et al, 2017).

The system of equations for the populations of ro-vibrational energy levels of the ground electronic state of H_2

Spontaneous emission

$$\frac{dn_l}{dt} = \sum_{m\neq l}\beta_{lm}n_m - n_l\left(\sum_{m\neq l}\beta_{ml} + \beta_{diss,l}\right) - n_l k_{\mathrm{H}_2,l} + \sum_{m>l}A_{lm}n_m - n_l\sum_{m<l}A_{ml}$$

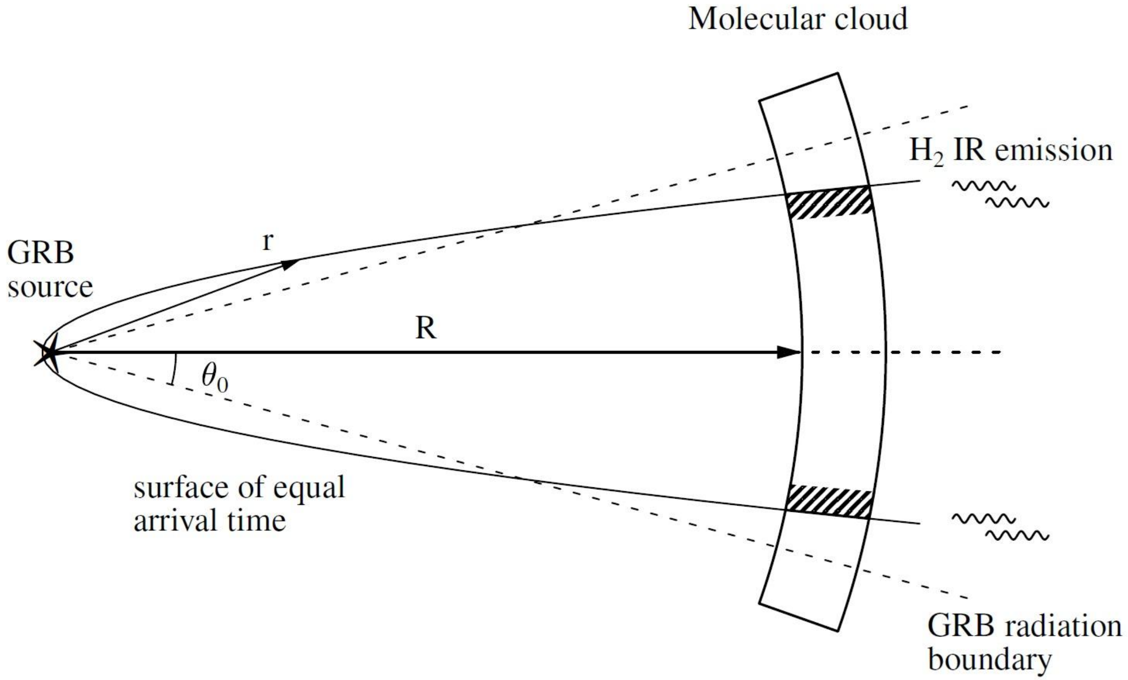
Effective rate of the *m* → *l* transition due to the photoexcitation of H_2 electronic states

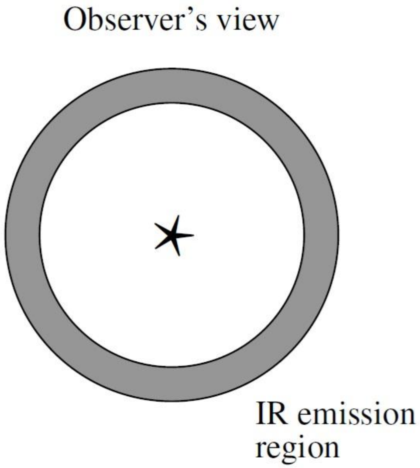
About 15% of electronically excited H_2 molecules dissociate

H_2 destruction due to photoionization and photodissociation

- The cloud is divided into spherical layers of equal thickness. For each cloud layer, the simulations are carried out of the photoionization and photodissociation of gas species, dust evaporation;
- The differential equation system is solved using the SUNDIALS CVODE v5.7.0 equation solver (Hindmarsh et al, 2005; Gardner et al, 2022);
- The simulations of the propagation of gamma-ray burst radiation in molecular cloud are published by Nesterenok (2024a,b);

H_2 infrared emission of molecular cloud induced by gamma-ray burst





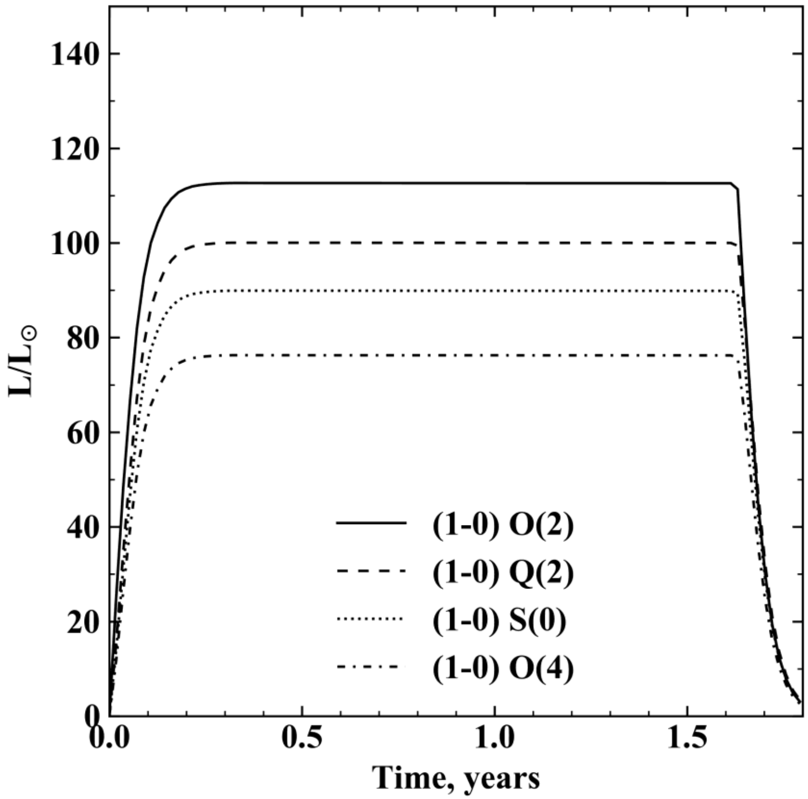
Model parameters:

- distance between the GRB source and molecular gas is R = 100 pc;
- hydrogen column density $N_H = 3\times10^{21}$ cm^{-2};
- H_2 concentration $n_{H2} = 10^3$ cm^{-3};
- jet opening angle $\theta_0 = 5° \approx 0.1$ rad;

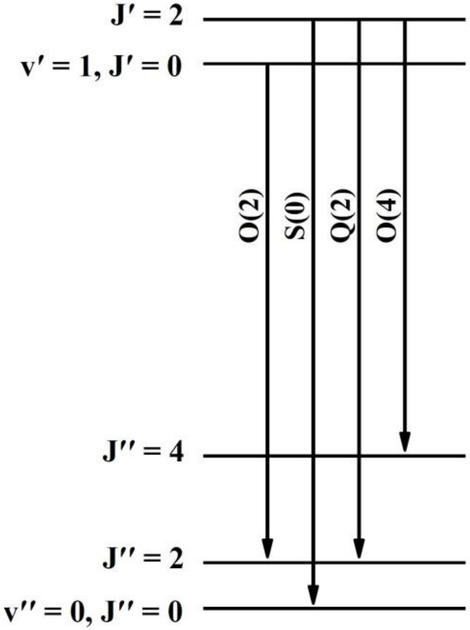
Delay time of the H_2 infrared emission:

$$t \approx R(1-\cos\theta)/c \approx$$
$$\approx \frac{R\theta^2}{2c} = 1.5\left(\frac{R}{100\,pc}\right)\left(\frac{\theta}{0.1\,rad}\right)^2\ years$$

Luminosity of H_2 lines induced by gamma-ray burst



para-H_2 transitions



$$\frac{L}{4\pi D^2 \Delta\Omega} = 10^{-6}\left(\frac{100\ Mpc}{D}\right)^2\left(\frac{L}{100\ L_\odot}\right) \text{ erg s}^{-1}\text{ ster}^{-1}\text{ cm}^{-2} > 10^{-8}\text{ erg s}^{-1}\text{ ster}^{-1}\text{ cm}^{-2}$$

(the redshift for D = 100 Mpc is z = 0.023;
$\Delta\Omega$ is angular resolution of JWST)

(JWST sensitivity for a signal-to-noise ratio of 3 over 1.25 h of integration)

Conclusions

- A model is constructed for the passage of a gamma-ray burst through a molecular cloud located at some distance in the parent galaxy.
- The UV emission of the gamma-ray burst photoexcites H_2 molecules to electronic states. The H_2 molecules decay back to the ground electronic state to vibrationally excited levels.
- We estimated the luminosity of infrared ro-vibrational transitions of H_2 that are photoexcited by UV radiation of the gamma-ray burst. This infrared emission may be detected by the *James Webb* Space Telescope for nearby gamma-ray bursts.