On the origin of gamma-ray bursts

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Gamma-ray bursts are the most energetic explosions in the Universe, occurring at cosmological distances. The initial phase of the emission from these bursts is predominantly of gamma rays and stems from a highly relativistic outflow. The nature of this emission is still under debate. Here, I present the interpretation that the peak in the photon spectrum can be attributed to the black-body emission of the photosphere of the outflow, having a temperature of approximately $10^9$ K. An additional non-thermal spectral component can be attributed to additional dissipation of the kinetic energy in the outflow. This two-component model can be well fitted to most instantaneous spectra. Interestingly, the thermal component exhibits a recurring behaviour over emission pulse structures. Both the temperature and the energy flux vary as broken power laws. During the pre-break phase, the temperature is approximately constant while the energy flux rises. Furthermore, the ratio of the observed thermal flux to the emergent flux increases as a power law over the whole pulse. It is argued that these observations hold the key to our understanding of the prompt emission and the properties of the site from which it emanates.

Keywords: gamma-rays bursts; thermal emission; non-thermal emission

1. Introduction

A few times every day the Earth is hit by a short and powerful burst of gamma rays, emanating from a random direction on the sky. The otherwise almost dark gamma-ray sky is then completely flooded with $\gamma$-ray photons. The radiation is so intense that it temporarily dominates all other celestial sources of $\gamma$-rays by several orders of magnitude. These flashes originate in the most luminous explosions in the Universe ever to have been detected by man, the gamma-ray bursts (GRBs). During the tens of seconds they are active, their energy output is comparable with that of the Sun over approximately $10^{10}$ years, i.e. the full age of the Universe. GRBs are now known to emit in all wavelengths, albeit the main part of the energy is in the mega electron volt (MeV) energy range, i.e. $\gamma$-rays made up of very high-energy photons. By comparison, a visible photon from the Sun has an energy of only a few eV. Every GRB photon thus contains one million times more energy.

Since the major part of the radiation cannot penetrate the Earth’s atmosphere, X-ray and $\gamma$-ray detectors flown on satellites are needed to detect them. Indeed, the research on GRBs is mainly observationally driven in that the major

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advances are made by new and more sensitive instrumentation. Based on this observational material, we now know that GRBs are predominantly located at great, cosmological distances from us, of the order of gigaparsecs ($10^{28}$ cm), comparable with the most distant galaxies and quasars. This corresponds to a time when the Universe was only a few tens of per cent of its present age.

The current understanding of the GRB phenomenon is that the bursts originate from the release of gravitational energy in a very small region (tens of kilometres) over a short time interval (seconds). At present, the most widely accepted model for the majority of GRBs involves a core collapse of a very massive, rotating star (approx. 30 times more massive than our Sun). This is similar to what happens in a supernova explosion, but under circumstances in which the core becomes too heavy to form a stable neutron star. The bursts are observed to stem from faint galaxies and to be associated with star-forming regions, which favours a scenario with a massive star explosion rather than, for instance, the merging of compact objects. The result is a rapidly spinning black hole with an ultra-magnetized disc orbiting around it, which in its turn is surrounded by the stellar remnant. As material falls into the spinning black hole, the system works similar to a giant electric motor, enormously powerful. The gravitational energy liberated in the accretion is focused into and drives jets of electromagnetic radiation, magnetic fields and particles moving at a speed close to the speed of light, outward along its rotation axis. Often this speed is measured by the Lorentz factor $\Gamma \equiv (1 - \beta^2)^{-1/2} \sim 100$, where $\beta = v/c$, the material speed divided by the speed of light. The explosion is thus highly anisotropic. This jet could pierce the surrounding gas and be observable as a GRB when the jet happens to point towards Earth. Various physical processes extract the energy in the jet and convert it into the $\gamma$-rays that we observe. However, a complete understanding of the origin has still not been fully reached.

The finding of GRBs was a truly unexpected discovery, maybe even serendipitous. The satellites that made the first identifiable detection were aimed to monitor clandestine nuclear weapons tests. In August 1963, the USA and the Soviet Union signed the Limited Test Ban Treaty, which banned nuclear weapon tests ‘in the atmosphere, in outer space and under water’. The US Department of Defense developed a series of Vela satellites (from velar = to watch in Spanish) to be able to monitor compliance with the Treaty. As mentioned previously, the Earth’s atmosphere is opaque to $\gamma$-rays, since these ionize atoms. Therefore, the emission from a nuclear detonation in space will be visible only from such satellites. The earliest Vela satellites were purely research instruments, aimed at determining the behaviour of the unknown X-ray and $\gamma$-ray background, on which the nuclear explosion signal would be detected. At the time, the high-energy Universe was thought to be more or less unchanging. In 1969, the initial data analysis started at Los Alamos National Laboratory. By using the fact that several Vela satellites were taking data at the same time, Klebesadel realized that some of the bumps in the data were not background, since he identified nearly simultaneous events observed by several satellites, and these had almost the same distribution of intensity over time. Further analysis could eliminate the Sun and the Moon, as well as the Earth, as their origin. The records were also uncorrelated with known solar or novae supernovae activities. Klebesadel et al. (1973) were therefore able to show that the bursts actually were from outside the Solar System, and that they represented a hitherto unobserved phenomenon involving.

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enormous amounts of energy. This spectacular discovery was announced in a paper in the *Astrophysical Journal Letters* in 1973. No official announcements of the detection of clandestine nuclear weapon tests were ever made.

Later detectors were designed to give increasingly better spectral and temporal resolution, in particular, of the prompt phase in the energy range of 20 keV to 2 MeV (where most of the energy is emitted). More than 3000 bursts have been observed. A striking finding is that no two light curves look exactly alike. A burst may last for 30 ms or several thousand seconds, and consists mainly of several pulse structures with a rapid rise and a slower decay phase. Furthermore, the radiation from the prompt flash in a GRB is observed to be distributed as a continuous spectrum over a broad energy range, without any emission lines. This is suggestive of non-thermal emission processes, for instance, synchrotron emission that arises as energetic electrons gyrate in magnetized plasmas. As we will see below, this is in fact not necessarily the whole story. Before discussing this in more detail, I will discuss how the GRB spectrum is observed to vary with time as the burst evolves.

2. Spectral evolution in GRBs

The observed energy distribution of photons (the spectrum) varies dramatically during a burst. This behaviour carries important information on the radiation process itself as well as on the dynamical evolution of the emitting region. For instance, this fact has been successfully used to explain the burst afterglow, which is the emission detected after the initial burst and which is conveyed by the photons of lower energies such as visible and radio photons. The afterglow is dominant from approximately 100 s to weeks, and even several months, after the initial trigger. Indeed, the afterglow emission has been shown to be explained by synchrotron emission from the expanding shell of matter in the outflow from the collapsing star. When it starts to interact with the circumburst medium, a shock is established in which electrons are energized and accelerated. The electrons cool rapidly as they gyrate in the local magnetic field, giving rise to the radiation that we observe.

The prompt flash is assumed to be created close to the explosion as the highly relativistic, unsteady outflow gradually becomes optically thin and energy dissipation processes within the flow itself cause particles to be accelerated. Magnetic fields at the emission site may indeed be strong and be caused by a frozen-in component transported by the outflow from the progenitor, or may be built up by turbulence. The spectral distribution emitted then depends on the details of the radiation mechanism, particle acceleration and dynamics of the explosion itself. It is important to note that the strong spectral evolution here also means that the time-integrated spectrum, for instance over a pulse structure, differs significantly from the instantaneous (time-resolved) spectrum. It is the latter that directly reflects the radiation process. It is therefore important to study the time-resolved emission. However, observers are forced to integrate the emission over a minimum period of time, in order to gather enough photons to be able to make a statistically stringent analysis.

It was already discovered in the early 1980s that the time-resolved spectra in general soften with time, which means that the dominating photons have less and less energy. A number of common trends and correlations have since been identified: for instance, successive pulses are usually softer, and the bursts for
which the bulk of the flux comes well after the trigger also tend to be softer. The softening over the burst can, in some cases, be spectacular and have a complex behaviour. Often there is a correlation between the spectral hardness and the intensity. In most pulses, the hardness decays monotonically as the flux rises and falls, creating the hard-to-soft pulses, while in some pulses the hardness follows, or tracks, the intensity, creating the tracking pulses. Beside the general trends, there are examples of bursts with very diverse behaviours. There are also a few cases that exhibit soft-to-hard and even soft-to-hard-to-soft evolution.

Golenetskii et al. (1983) quantified the tracking behaviour between the intensity and the hardness, which is most pronounced in the decay phase of pulses. Over the whole burst (several intensity pulses), there is often no pure correlation, even though the tracks in the hardness–intensity plane are confined to an area from hard and intense to soft and weak, indicating an overall trend of increasing luminosity with hardness. They found the power-law relation between the instantaneous luminosity and the power peak energy \( E_{pk} \), with the power-law index typically being 1.5–1.7. Later, Kargatis et al. (1994) and Borgonovo & Ryde (2001) confirmed the existence of the Golenetskii correlation in many pulses. The spread of the correlation index was substantially wider, 2.0 \( \pm \) 1. Furthermore, by studying the relation between the instantaneous hardness \( E_{pk} \) and the running time integral of the flux, the fluence, a clear correlation is often revealed over the entire pulse. Liang & Kargatis (1996) consequently found an empirical relation where \( E_{pk} \), over a single pulse, decays exponentially as a function of the fluence, \( \Phi(t) \). The decay index, \( \Phi_0 \), was found to vary between bursts and to have a lognormal distribution around log \( \Phi_0 \) \( \approx \) 1.75 (Crider et al. 1999). Neither the hardness–intensity correlation nor the hardness–fluence correlation includes the time dependence of the spectral evolution. However, combined they do, since the fluence is the time integral of the flux. This was used by Ryde & Svensson (1999) to synthesize and find a compact and quantitative description of the time evolution of the decay phase of a GRB pulse and show that the decay phase of the pulse should follow a power law.

The shape of the time-resolved spectra also varies. It is common to model the \( \gamma \)-ray spectra with a broken power law, an empirical model that fits the observations well. The spectrum is then characterized by the photon energy of the spectral peak, \( E_{pk} \), and two power-law indices. Of specific interest is the value of the photon distribution below the peak. It is found that more than half of all bursts exhibit substantial evolution in the low-energy power-law index, \( \alpha \), over the burst, mainly by becoming softer. Furthermore, \( \alpha \) most often follows the evolution of the peak energy, for both hard-to-soft pulses and tracking pulses. The averaged values of the power-law slope during the rise phase of the pulses are significantly harder for the hard-to-soft pulses, with many having a positive value and some even consistent with a black-body spectrum. The spectral shape above \( E_{pk} \) also varies, but not by as much.

3. Non-thermal models for the \( \gamma \)-ray spectrum

GRBs emit over a wide range of energies, which is a characteristic of non-thermal emission. Based on this fact, in combination with the success of the synchrotron model for the afterglow emission, it was early argued that optically thin
synchrotron radiation from shock-accelerated, relativistic electrons would be responsible for this emission as well. It is, indeed, very probable that shocks develop in the relativistic outflow, in which particles are accelerated to high energies (the internal-shock model). Alternatively, the acceleration can take place in magnetic reconnection sites. As the electrons gyrate in the magnetic field, they efficiently lose their energy, radiating the observed \( \gamma \)-rays. Acceleration scenarios most commonly lead to the density of the electrons being a power law as a function of electron Lorentz factor \( \gamma_e \), with the power-law index \(-p\) above a minimum value, \( \gamma_{\text{min}} \). Such a distribution gives rise to a photon flux spectrum with power laws of index \( \alpha_2 = \frac{2}{3} \) below a peak energy \( E_{\text{pk}} \propto \gamma_{\text{min}}^2 \) and a high-energy power law of index \(-p+1/2\) above it.

A serious problem with this scenario is that it has difficulties in explaining some observed spectral shapes. In particular, a substantial fraction of the instantaneous spectra have \( \alpha > -2/3 \), which is not possible in the model in its simplest form, since \( \alpha = -2/3 \) is the value of the fundamental synchrotron function for electrons with an isotropic distribution of pitch angles. The problem becomes even more severe for the case when the electrons cool quickly compared with the typical dynamic time scale of the outflow. In the typical setting of GRBs, having a relativistic outflow with a bulk Lorentz factor \( \Gamma \sim 100 \), the time scales for synchrotron and inverse Compton losses are approximately \( 10^{-6} \) s, which is much shorter than both the dynamic time scale (approx. 1 s) and the integration time scale of the recorded data, typically 64 ms to 1 s. In such a case, the low-energy power law should be even softer, with \( \alpha = -1.5 \), now contradicting the majority of the observed spectra. In the synchrotron model, it is indeed possible that the hard spectral slopes are due to synchrotron self-absorption, i.e. the electrons absorb the photons themselves, which would lead to harder spectral slopes in the photon fluxes; \( \alpha = 1 \) or 3/2. However, to get a high optical depth to self-absorption in \( \gamma \)-rays, somewhat extreme parameters have to be used; in particular, one needs to invoke a very high magnetic field; approximately \( 10^8 \) G for typical parameters.

Another efficient non-thermal radiative mechanism is inverse Compton scattering: the gamma-ray spectrum could instead be an inverse Compton image of the synchrotron spectrum, now located in the optical wavelength region since the energy increases as \( \gamma_e^2 \). The low-energy slope will be the same as for the synchrotron seed spectrum, \( \alpha < -2/3 \). But if the latter is self-absorbed, a situation that now requires much lower magnetic field strengths, the low-energy spectrum could be as hard as \( \alpha = 0 \). However, the spectrum around its peak is notably broader than what is observed. Alternatively, the inverse Compton emission could be seeded by soft photons with a narrow energy distribution, i.e. a quasi-mono-energetic distribution, producing a less broad spectrum and with a limiting value again at \( \alpha = 0 \). Compared to synchrotron emission, such an emission mechanism also alleviates the requirements on the magnetic field. Yet another alternative is the small pitch-angle synchrotron emission and similarly jitter radiation, which also produce hard spectral slopes, \( \alpha < 0 \). Here, the \( \gamma_e \)-dependent distribution of pitch angles is needed as well as a scenario to set up a distribution for which the pitch angles are not much greater than \( \gamma_e^{-1} \). This could be done by rapid cooling and inefficient diffusion transverse to the magnetic field. The latter two models are thus the main contenders for describing the prompt phase with a purely non-thermal model. Diffusive shock
acceleration (Fermi processes) is assumed to accelerate electrons from a shocked thermal population into a non-thermal distribution, which cools by these mechanisms and emits the observed radiation. Both of these emission processes need an almost purely non-thermal electron distribution to be able to fit the observed spectra. This is difficult to reconcile with shock models, which often have a strong contribution of a thermal population (Baring & Braby 2004).

Another complication for the synchrotron model arises in explaining the observed correlation between the peak energy of the burst and luminosity, also known as the Amati relation (Amati et al. 2002); the peak energy is correlated with the isotropically equivalent energy $E_{\text{pk}} \propto E_{\text{iso}}^{0.40 \pm 0.05}$. For the synchrotron, internal-shock model, one expects $E_{\text{pk}} \propto \Gamma^{-2} L^{1/2} t_v^{-1}$, where $t_v$ is the typical variability time scale and $L$ is the luminosity. This requires that both $\Gamma$ and $t_v$ are fairly similar for all bursts, which is difficult to imagine. In addition, assuming a typical $L \propto \Gamma^2$ would even lead to an anticorrelation. Additional assumptions are needed to explain the positive correlation.

4. Quasi-black-body model for the $\gamma$-ray spectrum

(a) Motivation

Both Goodman (1986) and Paczyński (1986) discussed optically thick outflows in connection with GRBs and the emergence of a black-body spectrum. Later, Mészáros & Rees (2000) examined the relative roles of such a photosphere and the non-thermal shock emission in the internal-shock model and presented a variety of spectra that could be expected. Such thermal–non-thermal hybrid emission is indeed common in astrophysical sources and is a natural consequence of heating of a background plasma and acceleration of particles. In essence, the density at the base of the relativistic outflow in GRBs should be so large that the optical depth to Thompson scattering by the baryon-related electrons is high enough to provide thermal equilibrium. Therefore, radiative processes occurring close to the base of the flow, and/or in the outflow while it is sufficiently optically thick, will thus emerge as a quasi-black-body spectrum.

The thermal pressure of the initial energy deposit will drive the outflow and accelerate it until it either becomes optically thin or reaches the terminal Lorentz factor $\Gamma = E/Mc^2$, where $E$ is the energy deposited and $M$ is the mass of the baryons in the flow. The flow will be advected through its photosphere; at the photosphere, the photons entrained in the flow will decouple from it and thus the photosphere is the location from which the photons can stream towards the observer without interacting. The location of the photosphere depends on the initial parameters of the flow, for instance, the initial temperature and the baryon loading, and can thus be time dependent. The radius from which the jet is launched could be close to either the black hole (typically $10^7$ cm) or the surface of the progenitor star (Wolf–Rayet star, approx. $10^{10} - 10^{11}$ cm) as suggested by Thompson et al. (2007). As the flow is accelerated, the thermal energy is converted into kinetic energy. Therefore, at the photosphere, there will always be a residual thermal component. Its size depends on where the photosphere occurs: the further away from the base, the lower the fraction. It is therefore a reasonable assumption that the early-time spectra do have a thermal component.
The kinetic energy of the flow will further be subject to dissipation mechanisms, e.g. shocks occurring in the unsteady flow or magnetic reconnections. This dissipation transforms the ordered kinetic energy of the flow into random energy that goes into magnetic fields and accelerated electrons. These cool by emitting the observed $\gamma$-rays, producing the non-thermal component. The exact nature of this dissipation is not known. The emission could, for instance, be synchrotron emission from the shock-accelerated electrons. Alternatively, the thermal emission can act as seed photons for inverse Compton scattering by these electrons. The resulting non-thermal component can therefore take a variety of shapes. For further detailed discussions on possible shapes, see Rees & Mészáros (2005) and Pe'er et al. (2006).

If we are indeed observing the photospheric emission, as suggested by the discussion above, it greatly simplifies the physical interpretation since we are detecting the fireball and its evolution directly. This is in contrast to the internal shocks that give us indirect information through the dissipation processes, randomly distributed throughout the fireball wind, which of necessity complicates the interpretation.

(b) Observations

One can indeed argue that a strong thermal component is important in shaping the observed $\gamma$-ray spectra of the prompt GRB. Most of the strong, pulsed bursts that I have analysed (most in the 20 keV to 2 MeV range) could be described by a two-component model consisting of a thermal component, modelled by a Planck function, and a non-thermal component, modelled by a power-law function, the sum of which creates the observed spectral shapes and evolutions (e.g. Ryde 2004, 2005). The typical peak in a GRB spectrum is thus caused by the photospheric emission. The behaviours of the two separate components on their own are, in general, similar from burst to burst, while the combined behaviour leads to the large variety in spectral evolutions that is observed. For instance, the hard low-energy slopes as well as the dramatic change in them are readily explained. The properties of the black-body emission further provide a natural correlation between the flux and the temperature that will underlie the Golenetskii and Amati relations. By comparison, the corresponding relation for synchrotron emission is more complicated and requires additional assumptions. Finally, it should be noted that the actual shape of the spectral components could be different from an exact Planck and power-law function. For instance, the thermal component might be made narrower by scattering, while several broadening effects could take place as discussed by, for example, Blinnikov et al. (1999).

As mentioned above, the non-thermal component is expected to have a non-trivial, broad-band shape, even though a power law fits the analysed energy range well. An extrapolation of the model beyond the fitted data should therefore be made with care (e.g. Ghirlanda et al. 2007).

Of particular interest is the behaviour of the thermal component. It is commonly observed that, during the energy flux increase of an individual pulse, the temperature remains almost constant or has a weak decay. After the flux peak, the temperature drops more rapidly. Both the temperature and the flux are well described by broken power laws. Even though individual cases have somewhat varying power-law indices, the average value of the temperature decay
after the peak is $-0.7$. Figure 1 shows a few examples of the temperature evolution during GRB pulses. These examples reflect the typical behaviours and the variation that is observed. The break in the temperature curve occurs approximately at the peak of the energy flux.

To further characterize the photospheric behaviour, Ryde & Pe’er (submitted) studied the dimensionless ratio $R \sim (F(t)/\sigma T(t)^4)^{1/2}$, where $F$ and $T$ are the flux and the temperature, respectively, and $\sigma$ is the Stefan–Boltzmann constant. The behaviour of this parameter is shown in figure 2, in which the corresponding light curves are presented as insets. $R$ is seen to increase monotonically, as a power law in time. A surprising feature is that there does not seem to be a strong break at the time when the flux and temperature break. $R$ increases as a power law over the entire pulse. An interpretation of $R$ is that it describes the transverse size of the emitting region, which according to these observations thus increases nearly monotonically over a pulse and a burst.

The distinct behaviours, shown here, most certainly hold the key to our understanding of the prompt emission and the photosphere. The recurrence of the behaviours over pulses of the temperature and the ratio $R$ is indeed

Figure 1. (a–d) Temperature decay over pulses in four different bursts, identified by their Compton Gamma-Ray Observatory (CGRO) Burst And Transient Source Experiment (BATSE) detector trigger numbers: (a) 2083, (b) 4556, (c) 5478 and (d) 6630. The temperature is initially around 100 keV (approx. $10^9$ K) and decays later as a broken power law. The temperature increase at approximately 8 s in 2083 is due to an additional pulse. Partly adapted from Ryde (2004).
remarkable. The interpretation of these behaviours is, however, not obvious and several suggestions have been discussed. The variations could be due to varying initial properties of the flow (temperature, baryon loading, etc.), or it could be dominated by geometrical effects, such as the high-latitude emission as suggested by Pe\'er et al. (2007). Further discussions are given in Rees & Mészáros (2005), Ryde et al. (2006) and in papers that we are preparing.

5. Future broad-band observations will be helpful

The current understanding of the prompt phase is based mainly on the rich data in the keV–MeV energy range. The narrowness of this energy range makes it difficult to identify clearly and unambiguously the origins of the emission. On a few occasions, the Swift satellite has provided a broad-band spectrum of the prompt phase, with its two instruments. Also the late-time flares, which are observed in the afterglow, can be further studied with this model. However, these detections must be sufficiently strong to make time-resolved spectroscopy in a satisfactory manner possible. In particular, the Gamma-ray Large Area Telescope (GLAST; now known as the Fermi Space Telescope) covers an energy
range of approximately 10 keV to approximately 200 GeV with its two instruments (GLAST Burst Monitor and the Large Area Telescope) and will probably provide a sufficiently broad energy range to make this possible.

If indeed the photospheric emission is decisive in the MeV range, the additional broad-band, non-thermal emission component would be visible in the high energy range. This will give us valuable information on its actual shape and evolution. Furthermore, it is probable that the radiation in the keV–MeV range scatters on the relativistic electrons in the outflow shocks, which will result in inverse Compton emission in the GeV domain. For instance, if the sub-MeV emission is due to synchrotron emission, synchrotron self-Compton processes will cause emission in the GeV range. Alternatively, the GeV energy range could be dominated by hadron-related emission via pion production and cascades; high-energy neutral pions ($\pi^0$) can be created as shock-accelerated, relativistic protons scatter inelastically off ambient photons ($p\gamma$ interactions). These later decay into $\gamma$-rays.

6. Conclusions

It is currently difficult to prove whether the prompt spectrum in GRBs can be described by any specific emission model. Here, I have been arguing for the interpretation that the peak in the GRB spectrum can be attributed to the black-body peak of the photosphere of the outflow and that the broad nature of the spectrum is due to an additional non-thermal component. There are several properties and arguments that make this interpretation attractive. From a statistical point of view, this model fits the data well, at least as well as any other model suggested so far. Furthermore, given the general picture of a GRB that has grown from other observations, a black-body component is reasonable from a physical point of view, and the parameters that are given from the fits are indeed reasonable. As shown above, this model alleviates many of the problems of the synchrotron interpretation. The behaviour of the thermal emission component is similar for most bursts, showing a recurring behaviour. The non-thermal component and its broader band shape can take a variety of shapes and should be investigated further.

The main observational consequences of the black-body interpretation of the $\gamma$-ray spectrum are the following. (i) The temperature decays as a broken power law with an initial slow decay, sometimes even being constant. While such a break in the temperature curve seems ubiquitous, the exact values of the slopes do vary. (ii) The energy flux contained in the black-body component rises during the constant-temperature phase, and later decays, in both cases as a power law. (iii) The ratio $R$ increases as a power law in time. This is the case both before and after the breaks in temperature and flux curves. This is indeed an unexpected behaviour. These properties hold the key to the understanding of the prompt emission phase.

References


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