LUMINESCENCE AROUND THE MR-12 METEOROLOGICAL ROCKETS IN FLIGHT

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Luminescence in the environment around MR-12 meteorological rockets was studied on the descending trajectory by two spectroradiometers installed in the rocket payload. The spectroradiometers had a field of view of 3°, the optical axis being oriented at 55° to the rocket spin axis and along it, respectively. The results of fourteen flights are considered. The extent of the region of the near-rocket glow (NRG) along the rocket trajectory is shown to increase as the flight altitude decreases. It is found that the daytime NRG consists of two components: the scattered sunlight portion produced by the rocket aerosol environment and an emissive one. The spectral characteristics of both NRG components are given. Day-to-night changes of the NRG characteristics and those induced by flight conditions are analyzed.

INTRODUCTION

Luminescence appearing around spacecraft and rockets in flight is now regarded not only as an interference during measurements, but also as an interesting phenomenon, attracting close attention and calling for dedicated studies. The phenomenon of near-rocket glow (NRG) was first detected in 1956 during studies of the atmospheric nighttime emissions in the visible range. It appeared along the rocket descending trajectory.[1] Heppner et al.[1] suggested a possible mechanism for this glow: the interaction between the molecules M of the rocket engines' residual exhaust gases, in particular, the molecules of nitrogen oxide, NO, with atmospheric atomic oxygen O:

$$NO + O + M \longrightarrow NO_2 + h\nu. \quad (1)$$

In the course of further studies it was found that the NRG phenomenon could hardly be explained by that reaction alone. Greer et al.[3] have reported nighttime observations of NRG in the UV range (275 and 320 nm) in addition to the visible and IR spectral intervals. At the same time the emission continuum, produced by the above-described process,[1] starts at 3875 Å.[2] Another paper[4] presents data on strong NRG in the IR along the ascending trajectory. Two reactions, at least, are suggested to be related to NRG,[3] one is responsible for emission in the 275–300 nm band, and the other – at wavelengths greater than 550 nm.

The NRG was recorded in all of the experiments over various spectral ranges along both the ascending and descending rocket trajectories. A review of the phenomena associated with the luminescence around the rockets and spacecraft may be found in Ref. 5.

Initially, the nighttime glow around the MR-12 rockets was detected in 1976 (see Ref. 6). Observations were conducted using surface-based TV systems. The glow was detected along the ascending trajectory at altitudes of from 83 to 130 km. The intensity of that glow reached its maximum between 98 and 120 km and was recorded as stellar magnitude of 5–6.

In Ref. 7 I demonstrated that an important mechanism of the daytime NRG around the MR-12 rockets is the scattering of solar radiation by the aerosol particles surrounding the rocket. The NRG was detected during descending trajectories during all of the launches. In individual cases this glow was also observed during the ascending trajectories. Nighttime and dusk NRG was significantly weaker than that observed during daytime. Such observations demonstrate that there exists, along with the aerosol scattering of solar radiation from around the rocket, an emission apparently resulting from interaction of the residual exhaust gases from the rocket engine with natural molecular components of the atmosphere.

The goal of the present paper consists of three parts: 1) to analyze the instrumental problems of recording the NRG from aboard the MR-12 rocket along its descending trajectory, 2) to use the results of this analysis to determine the contribution of emission and aerosol scattering to the daytime NRG, and 3) to study the spectral composition and variations of the NRG.

INSTRUMENTATION PECULIARITIES OF NRG RECORDING FROM ABOARD THE MR-12 ROCKET

The purpose of the spectroradiometers of the SR-184 and SR-185 types,[8] installed in the MR-12

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payload is to study scattered light and emissions in the upper atmosphere. However, they appear also to be quite effective for NRG studies. The rocket lifts its payload up to an altitude of about 150 km. The optical axes of the instruments are oriented at 55° to (SR-184) and along (SR-185) the rocket spin axis. The field of view of each radiometer is 3°. Because of the rocket spin the optical axis of the SR-184 instrument follows a 110° cone. The radiometer switches from channel to channel sequentially and it has both integrated (3000–6000 Å) and narrow band channels. The latter are centered around the following wavelengths: 3690, 4570, 5300, and 5760 Å. The channels of the SR-185 instrument are centered at 3914, 4278, 5700, and 5577 Å. The transmission bands of these narrow channels are formed by interference filters of $\Delta\lambda$ = 30–200 Å half-maximum bandwidths. The recording time per channel is 0.5 s and the interval between two successive measurements in one and the same channel is 6 s.

Figure 1a compares the NRG intensities of the SR-184 and SR-185 spectroradiometers (in relative units) from the B-60 daytime launch (the Sun's zenith angle at the moment of take-off was 91.9°). An important feature of this launch was that the rocket nutation angle was quite small (3°) at the cone top.

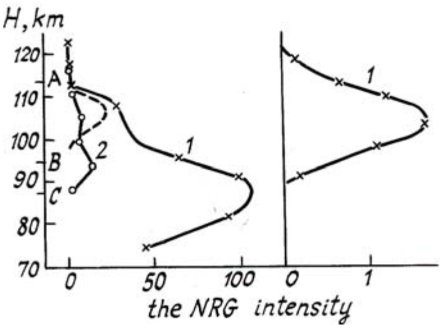


FIG. 1. Vertical profiles. of the NRG intensity in the integrated channel 0.3–0.6 μm *along the descending rocket trajectory: a) during the B-60 launch under daytime conditions for* $z_{\odot}$ = 91.9°: *1 — by the SR-184; 2 — by the SR-185; the dashed line denotes the emission component of the NRG (SR-184); b) during the Z-50 launch under nighttime conditions for* $z_{\odot}$ = 101.5°; *A, B, and C — altitudes corresponding to the three following times at which the NRG were recorded by the SR-185: beginning of the signal, its maximum, and signal vanishing to zero.*

The radiation intensity recorded by the SR-185 radiometer was averaged over every 0.5 s. The NRG intensity was determined from these data as the difference between the values recorded during the ascending and descending trajectories. From the SR-184 spectroradiometer data was determined the maximum NRG during every separate rotation of the spinning rocket (~ 0.2 s). These maxima corresponded to the position of the spectroradiometer optical axis at which the angle a between it and the vector opposite the total rocket velocity attained its minimum,

As can be seen Fig. 1a, the vertical profiles of the NRG intensity obtained from the two spectrometers differ significantly from each other on any given launch. The SR-184 signal maximum was obtained from an altitude of about 85 km, while the SR-185 instrument did not detect any emission from that altitude at all. The maximum of that radiometer signal was recorded at approximately 95 km.

The difference between these two profiles follows from the different orientations of their optical axes with respect to the luminescing volume, and is also due to spatio-temporal changes in the NRG.

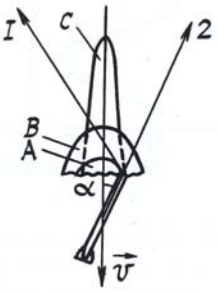


FIG. 2. Schematic representation of luminescing regions on the descending trajectory at the three altitudes A, B, and C corresponding to Fig. 1a. Indicated are the lines of vision of the SR-184 (1) and SP-185 (2) instruments, the rocket flight direction v and the angle a. between the direction opposite the rocket flight direction and its spin axis.

Figure 2 schematically shows the position of the luminescing zones with respect to the rocket position at the different altitudes A, B, and C. These altitudes correspond to three different times at which the NRG were recorded by the SR-185 (Fig. 1a): its beginning, when the luminescence does not differ too much from the background (altitude A); the moment when the signal reaches its maximum (altitude B), and the decay of the signal to zero, which happens when the luminescing zone leaves the instrument field of view (altitude C). The NRG profiles produced by both radiometers are plotted in Fig. 2. Since their optical axes were aimed into the upper hemisphere, no data on the NRG from the lower hemisphere were collected, and the zone of the NRG in the lower part of Fig. 2 is simply cut off by a wavy line.

In Ref. 7 I demonstrated that the NRG maximum from all of the MR-12 launches, as recorded by the SR-185 instrument, corresponded to that position of the rocket in its nutation at which the angle α was at its minimum (Fig. 2), i.e., the luminescence maximum in the NRG vertical profile was determined not by any physical mechanism of this luminescence generation, but by the geometric factor alone.

In contrast to the SR-185, the SR-184 instrument is capable of recording the emission along the entire descending trajectory down to the moment the rocket capsizes at 70–80 km: the emission zone does not leave the instrument field of view because it extends back along the rocket trajectory (Fig. 2).

For the emission zone to remain in the instrument field of view when it is extended so far back along the rocket trajectory, the angle at which the radiometer itself is set with respect to the rocket spin axis must obviously be larger than the angle between that axis and the rocket trajectory. At altitudes of about 100 km the declination of the rocket spin axis from the descending trajectory is within 13–35°. The chosen setting of the spectroradiometer optical axis relative to the rocket spin axis (55°) satisfies the above condition.

A consequence of these factors is that during the recording of the NRG its intensity dependence on the rocket nutation angle α is not as strong for the SR-184 instrument as it is for the SR-185.

Thus, the most complete data on the NRG within the total altitudinal range of the descending trajectory may be obtained by employing radiometers whose optical axes are set at an angle with respect to the rocket spin axis, and that angle should exceed the angle between the spin axis of the rocket and its trajectory.

Further analysis is based mainly on data obtained from the SR-184 spectrometer.

TWO COMPONENTS OF THE DAYTIME NRG AND THEIR VERTICAL LOCALIZATION

The daytime NRG may be represented as a combination of two components: the emitted component and the component scattered from the aerosol environment of the rocket. To retrieve the vertical profile of the NRG emission component and to evaluate the scattering contribution, we computed the vertical luminescence profiles from both the daytime and the nighttime launches.

Figures 1a and b respectively present the SR-184 vertical intensity profiles from the B-60 and the Z-50 launches. During the B-60 launch the rocket was illuminated by direct solar radiation, while during the Z-50 launch it flew in the Earth's shadow ($z_{\odot}$ = 101.5°).

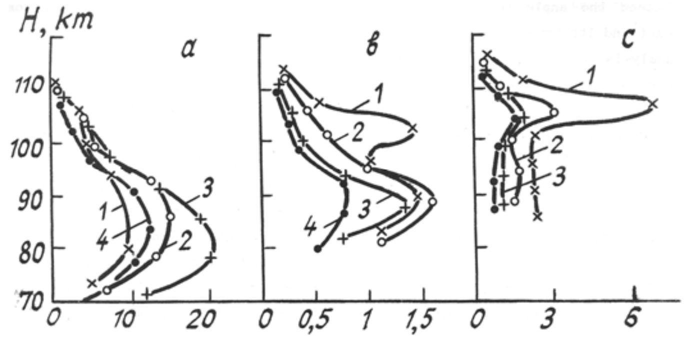
As can be seen from Fig 1, during the Z-50 nighttime launch the luminescence not associated with the scattered solar radiation was concentrated within the 100–110 km altitude range, while the B-60 daytime launch produced an overall emission maximum at about 85 km. Besides, at altitudes of 100–110 km there wasa local emission maximum. It is natural to associate the 100–110 km maximum with the NRG emission component. In Fig. 1 this component is indicated by a dashed line, as distinguished from the overall NRG during the B-60 launch.

The 100–110 km maximum of the NRG was detected during numerous MR-12 launches, and even when the rocket nutation was significant (about 10°) that maximum did not depend on the extrema of the angle α. By all appearances, this local maximum in the vertical profile of the NRG intensity is associated with photochemical interaction of the rocket exhaust with the atmospheric atomic oxygen, whose maximum concentration is known to localize at about 100 km.

The NRG maximum around 85 km (see Fig. 1) is produced by solar radiation scattered by the aerosol particles which interact with the oncoming air flux. As I noted in Ref. 7, the molecules and particles surrounding the rocket are, by all appearances, the products of the rocket solid fuel combustion, and are emitted from the rocket nozzle. When the rocket enters the atmosphere they are hit by the oncoming air flux, all of which takes place within the instrument field of view. Problems associated with the deformation of the gas-particle cloud at various altitudes and with the reaction of particles of different sizes to that stream were analyzed in detail in Ref. 7 on the basis of data from several MR-12 launches.

The NRG maxima associated with the scattered solar radiation are altitudinally localized around 80–90 km, as shown by the data from the SR-184 observations which were obtained during several launches.

The existence of two NRG generation mechanisms is testified to by the data on the radiation spectral composition and on the scattering phase function effect, to be considered below.



the NRG intensity

FIG. 3. Vertical profiles of the NRG intensity in the spectral channels 1) 3690 Å, *2)* 4570 Å, *3)* 5300 Å, *4)* 5760 Å *in the following rocket launches: a) B-60, b) B-53, c) Z-44.*

THE SPECTRAL COMPOSITION OF THE NRG

Figure 3 presents vertical profiles of the NRG intensity (relative units, proportional to the reference battery voltage) in various spectral channels of the SR-184 spectroradiometer, obtained from three daytime launches. Figure 3a corresponds to scattered light dominating in the recorded NRG. Figure 3b presents another case, in which contributions from both the emitted and the scattered components of the NRG are comparable to each other. The case in which the emitted radiation dominates in the NRG is illustrated in Fig. 3c.

According to Fig. 3 the NRG may be represented as consisting of two spectral components, each with its own spectral composition and vertical localization. The local NRG maximum at around 100–110 km, produced by its emission component, is most strikingly manifested at λ = 3690 Å. In that range around 80–90 km (note that the scattered light is detected at these altitudes) the UV contribution to the NRG is much less. In other words, the spectral differences between the two components are manifested primarily in the UV range.

Table I lists the data on the spectral composition of the NRG emission component obtained from an altitude of around 102 km during the Z-44 (Fig. 3c, daytime, SR-184 data), and the B-66 (nighttime, SR-185 data, $z_{\odot}$ = 108°) launches.The measurement errors were about 15–20%.

TABLE I. The NRG emission component intensity, relative energy units.

Launch number	λ, Å						
	3690	3914	4278	4570	5300	5577	5760
B–66	—	7.1	4.1	—	1.0	1.1	—
Z-44	6.6	—	—	3.3	1.0	—	1.9

The studies of the wavelength dependence of the NRG spectral characteristics within those altitude ranges and under those conditions in which the emission component was not large demonstrate that the emission intensity I obeys the following law: $I \sim 1/\lambda^{\gamma}$, where γ varies from 3–4 to 0. For example, the B-53 launch (Fig. 1b) yielded the result $I \sim 1/\lambda^3$ at about 92 km, while the B-60 launch (Fig. 1a) yielded the dependence $I \sim 1/\lambda^0$ at 90 km, i.e., the radiation intensity is independent of the wavelength in the latter case.

The exponent in the above power law is known to depend on the size of the light scattering particles. As γ varies from 4 to 0 the particle size changes from very fine (about 0.01 μm) to coarse (about 1 μm) and even further, during which the particle scattering cross section increases rapidly. Naturally, this all depends on the studied spectral range.

Comparing the NRG spectral characteristics around 90 km, obtained from the data from the B-60 and the B-53 launches, one may conclude that during the latter launch the solar radiation was scattered by particles finer than those present during the B-60 launch, and that the scattered light intensity during the latter launch was significantly greater.

THE SCATTERING PHASE FUNCTION EFFECT

The intensity of the scattered radiation varies slowly with the scattering angle θ for fine particles, following the $1 + \cos^2\theta$ dependence. Meanwhile, the same dependence for coarse particles, is much stronger.

It was shown in Ref. 7 that the effect of a sharp "spike" in the brightness signal obtained from the B-60 launch at small scattering angles, when the gas-particle cloud, in which coarse particles were present, entered the plane containing the rocket spin axis and the Sun. The same effect, which we have called the scattering phase function effect is apparently manifested in the following feature. In those cases in which the rocket was moving toward the Sun, and the gas-particle cloud was not between the Sun and the rocket, the contribution of the scattered radiation to the NRG was sharply diminished, since the scattering angles in this case were large. The Z-44 launch may serve as an example of this (see Fig. 3c).

The scattering phase function effect testifies to the existence of a scattered NRG component produced by the aerosol environment of the rocket.

TABLE II. The maximum NRG intensities (λ = 3690 Å), *relative energy units.*

Launch number	Z-50	B-49	B-51	B-52	B-53	B-54	B-56
Intensity	0.4	7.7	0.9	1.4	1.4	1.0	1.7

Launch number	W-60	Z-40	Z-41	Z-42	Z-44	Z-45	Z-59
Intensity	10.0	2.5	1.8	19.0	6.7	3.4	5.0

NRG VARIATIONS

Table II presents the maximum NRG intensities (relative units) obtained during several launches from the SR-184 instrument in the λ = 3690 Å spectral channel. All the launches, except Z-50, took place during daytime.

Note that according to certain estimates, due to the variability of the geometric factor the spread in the values of the NRG intensity in this series of launches did not exceed 1.5–2.

It can be seen from Table II that the daytime NRG's may be increased by more than an order of magnitude in comparison with the nighttime values. However, to obtain a more accurate estimate of the daily NRG intensity variations, it is necessary to accumulate more nighttime observations. The daily variability of the NRG emission component are even more difficult to estimate since one needs to separate the two NRG components to do that, and it is not always possible to do this with sufficient accuracy.

Without question, the daytime intensification of the NRG during several launches resulted from the scattering of solar radiation by the aerosol environment of the rocket. For example, the strongest luminescence observed during the Z-42 and the B-60 launches was associated mainly with aerosol scattering. This conclusion is supported by data on the spectral composition and the vertical localization of the emission, and also by the scattering phase function effect observed during these launches. The emission component was present in every launch, and the scattering mechanism manifested itself in several other launches as well, although not so spectacularly as during the above two.

As already noted, one of the prerequisites for stronger scattering is the direction the rocket is flying in: it has to be either in the solar or the anti-solar direction. Note that during the B-60 and the Z-42 launches the rocket was flying in the anti-solar direction, while during the Z-44 and the Z-45 launches the situation was exactly the opposite. Both the vertical localization and the spectral composition of the NRG point to emission dominating during the latter two 1aunches.

CONCLUSION

We conclude from our studies of the glow surrounding the MR-12 rockets that the NRG zone extends along the descent leg of the rocket trajectory. Because of this tendency the NRG may be detected along the entire descent portion of the trajectory (prior to the rocket capsizing) by radiometers mounted at an angle to the rocket spin axis greater than the angle between that axis and the trajectory. In particular, the SR-184 spectroradiometer fits this condition.

It has been established that the daytime NRG may be divided into two components: one due to scattering by the aerosol particles surrounding the rocket, and the other, the "true emission" one. Depending on the time of day, the launch conditions, and the number density and size spectrum of the particles around the rocket, one or the other component may dominate.

The SR-184 instrument detected the emission maximum at altitudes of 100–110 km in the majority of launches, however, the scattered radiation maximum localized at 80–90 km.

The spectral characteristics of both the emitted and the scattered components of the NRG have been obtained. It has been shown that the emitted radiation is most intense in the UV range, with its maximum intensity being recorded at 3690 Å. The scattered intensity wavelength dependence (normalized to the solar radiation intensity) follows the law $I \sim 1/\lambda^{\gamma}$, where γ varies from 3–4 to 0 from launch to launch. It has been shown that scattering is detected mostly when the rocket is flying away from the Sun, causing the aerosol cloud to be situated between the Sun and the rocket. The NRG may increase by an order of magnitude or more during the daytime. However, more nighttime observations are needed to carry out a more detailed analysis.

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