Ambient light emission from hydrothermal vents on the Mid-Atlantic Ridge

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Received 22 February 2002; accepted 13 May 2002; published 13 August 2002.

[1] A spectral imaging camera was used to observe light emission from high-temperature, deep-sea vents at three hydrothermal sites on the Mid-Atlantic Ridge (MAR): Logatchev, Snake Pit, and Lucky Strike. Ambient light measured at these sites is similar to that observed at sites along the East Pacific Rise and the Juan de Fuca Ridge, with components from both thermal and non-thermal sources. The shrimp species *Rimicaris exoculata*, which is found on the MAR but not in the Eastern Pacific, possesses a unique photoreceptor capable of detecting low light levels. It is not yet known if *R. exoculata* "sees" vent light. However, since the characteristics of vent light appear to be unrelated to geographical location, the exclusion of *R. exoculata* from the Eastern Pacific is probably unrelated to differences in ambient light conditions. INDEX TERMS: 3035 Marine Geology and Geophysics: Midocean ridge processes; 4832 Oceanography: Biological and Chemical: Hydrothermal systems; 4847 Oceanography: Biological and Chemical: Optics; 4294 Oceanography: General: Instruments and techniques

1. Introduction

[2] The search for vent light was prompted by the discovery of a novel photoreceptor on the Mid-Atlantic vent shrimp *Rimicaris exoculata* [*O'Neill et al.*, 1995; *Van Dover et al.*, 1989]. This species of shrimp, and other species with similar photoreceptive organs, are not found along the East Pacific Rise or the Juan de Fuca Ridge [*Van Dover*, 2000]. Although a simple photometer was used to collect preliminary light data on the MAR in 1993 [*Van Dover et al.*, 1996], a detailed analysis of MAR vent light has not previously been performed. Thus, the question arises: Is the difference in biological communities (i.e., the lack of *R. exoculata* in the Eastern Pacific) due in part to different ambient light conditions? The pigment in *R. exoculata*'s photoreceptor absorbs maximally at 500 nm. However, the highest emission observed at vents in the Pacific is in the 700–1000 nm range and is due to thermal (blackbody) radiation which peaks in the infrared. Non-thermal light does exist in the visible region (350–750 nm) — in some cases with peaks around 500 nm — and is significantly higher than thermal radiation in this range. Nonetheless, the emission levels observed at these shorter wavelengths (<650 nm) are orders of magnitude less than the emission levels in the far-red to near-infrared region [*White et al.*, 2002].

[3] A spectral camera called ALISS (Ambient Light Imaging and Spectral System) was designed to obtain both spectral and spatial information about vent light in order to characterize it and determine its possible sources. ALISS was used to image a number of vents at 9°N on the East Pacific Rise and in the Main Endeavour Field of the Juan de Fuca Ridge in 1997 and 1998 [*White et al.*, 2002; *White et al.*, 2000]. At both locations, the dominant source of light at wavelengths >650 nm was found to be thermal (blackbody) radiation due to the high temperature of the exiting fluid. However, at shorter wavelengths, light from non-thermal mechanisms becomes more significant. The non-thermal sources that may contribute to vent light include chemiluminescence (due to chemical reactions such as sulfide oxidation [*Tapley et al.*, 1999]), crystalloluminescence and triboluminescence (due to the formation and fracturing of crystals, respectively [*Zink*, 1981]), and vapor bubble luminescence (due to the rapid quenching of macroscopic vapor bubbles [*Chakravarty and Walton*, 2001]). While the relative contributions of these non-thermal emission mechanisms cannot yet be quantified, they are known to produce significant light (orders of magnitude above that expected by thermal radiation alone) in the visible region of the spectrum.

[4] This paper presents the first data collected by the ALISS camera at high-temperature hydrothermal vents on the Mid-Atlantic Ridge. Vents on the MAR differ from those in the Eastern Pacific in depth (and hence pressure), chemistry, age and biological communities. Thus, it was hypothesized that the light emission from MAR vents would differ as well. In order to characterize light emission from these vents, ambient light measurements were made at vents which varied in temperature, depth, and associated biological communities from ~15°N to 37°N along the Mid-Atlantic Ridge. Preliminary analyses show that light emission from vents in the Atlantic is very similar to that from vents in the Pacific, being dominated by thermal radiation at long wavelengths and by time-varying, non-thermal light at shorter wavelengths (<650 nm). While the light emission at 500 nm (where photoreceptors on *R. exoculata* are most sensitive) is greater than that predicted by purely thermal radiation, it does not appear to be any greater at MAR vents than it is at vents in the Eastern Pacific.

2. Instrumentation and Data Processing

[5] ALISS is a CCD camera with custom-designed optics which allow it to image the same scene simultaneously in nine wavelength bands [*White*, 2000; *White et al.*, 2002].

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0094-8276/02/2002GL014977$05.00

The 1024 × 1024 pixel CCD chip is divided into nine ~300 × 300 pixel tiles by a set of baffles and lenses. Each lens is covered with an individual optical bandpass filter. ALISS contains two filter arrays of nine filters each which span the 400–1000 nm region of the spectrum (i.e., the visible and near infrared). Filter array #1 contains nominally 100 nm bandwidth filters centered at 450, 550, 599, 652, 705, 753, 792, 870 and 947 nm. Filter array #2 contains two 100 nm bandwidth filters centered at 492 and 902 nm, six nominally 50 nm bandwidth filters centered at 475, 577, 676, 780, 878 and 980 nm, and a 10 nm bandwidth filter at 589 nm. ALISS is positioned at a vent using the *Alvin* submersible, and three to five 5-minute exposures are obtained with each filter array. In some cases, a series of 30-second exposures is obtained to analyze the time-varying nature of the light. During imaging, all of *Alvin*'s external lights and lasers are secured, and the viewports are blacked out to prevent any light leakage from the sub. More details regarding operations can be found in *White et al.* [2002].

[6] ALISS images are processed using standard image processing techniques [see *White*, 2000; *White et al.*, 2002, and references therein]. This includes correcting for systematic errors such as bias and dark charge, flat-fielding to correct for pixel-to-pixel variations, and median averaging to reduce noise. A source mask and complementary background mask are created to isolate the area of light emission from the background. This mask is created from the tile with the highest signal-to-noise ratio (the 870 nm channel) and is applied to all of the other tiles. The source mask was divided into intensity quartiles to analyze how the spectrum varies spatially. Because thermal radiation is expected to dominate in the 870 nm channel, it is assumed that variation in intensity in this channel indicates variation in temperature. Therefore, the highest intensity quartile (the 75–100 percentile region) contains the hottest region (i.e., the vent orifice), and the lowest intensity quartile (the 0–25 percentile region) contains the coolest region.

[7] Count rates for each filter are determined by integrating over the source area and removing background levels. The integrated count rates for each filter as measured by ALISS must be converted into the spectrum at the source. The photon flux at the vent is related to the count rate measured at the ALISS camera by the equation

$$Flux_{vent} \cdot e^{-\kappa \cdot x} \cdot \frac{A_{eff}}{x^2} = CR_{ALISS} \cdot gain \qquad (1)$$

where $Flux_{vent}$ is the photon flux at the vent in photons/cm^2/sec/sr (steradians is the unit of solid angle), κ is the attenuation coefficient of seawater in cm^{-1}, x is the camera-vent distance (nominally 50 cm), A_{eff} is the effective aperture determined by calibration (which includes the quantum efficiency of the CCD chip and the transmission through the ALISS optics), CR_{ALISS} is the count rate measure by ALISS in counts/cm^2/sec, and the *gain* of the camera is 6.1 electrons/count. Since the filters are not perfect, A_{eff} induces some transmission at all wavelengths, and (1) cannot be inverted uniquely to obtain $Flux_{vent}$. Analogously to geophysical inversion, we seek the photon flux as a function of wavelength subject to an *a priori* constraint that fits the ALISS count rate data to within a specified misfit. A smoothest spectrum constraint was employed for the present work [see *White et al.*, 2002 for a detailed description].

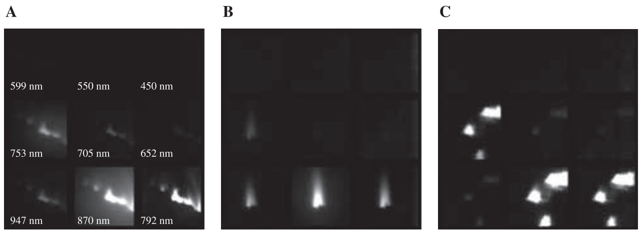

Figure 1. Ambient light images from filter array #1 of (a) Irina-2 smoker (348°C), Logatchev, (b) Beehive smoker (337°C), Snake Pit, and (c) 318°C smoker at Lucky Strike. The center wavelengths of the filters are noted on each tile in (a). The bandwidth of the filters is nominally 100 nm. Light intensity increases with increasing wavelength until the longest wavelength filter (947 nm) where attenuation becomes dominant. Each tile has a field of view of ~15 × 15 cm.

3. Geologic Setting and Ambient Light Emission

[8] ALISS was deployed at three sites on the slow spreading (~1.1–1.3 cm/yr half-rate) MAR during a July 2001 *Alvin* dive cruise: Logatchev, Snake Pit, and Lucky Strike. The MAR is characterized by a wide (~10–20 km) rift valley, occasionally with a neovolcanic ridge along the ridge axis.

[9] The Logatchev Hydrothermal Field is located at 14°45′N, 44°59′W along the eastern wall of the axial valley [*Sudarikov and Roumiantsev*, 2000]. Images were obtained of a small 348°C black smoker south of the central chimney complex at the Irina 2 site (near marker "A") at a depth of 3007 m (Figure 1a). Hydrothermal fluids are emitted along a small ridge (~10 cm wide in the ALISS image). The ambient light image shows significant emission above ~750 nm, and increasing intensity with increasing wavelength. This increase in intensity is the tail of the blackbody curve which peaks at ~4600 nm for a 350°C body. In the longest wavelength channel (947 nm — bottom left tile) the intensity decreases sharply as attenuation becomes dominant. Attenuation in seawater is lowest around 400–500 nm and increases rapidly in both directions (a more detailed discussion of attenuation can be found in *White et al.* [2002] and *White* [2000]).

[10] The Snake Pit Hydrothermal Field is located atop a neovolcanic ridge in the center of the rift valley at a depth of 3465–3512 m [*Fouquet et al.*, 1993]. A 337°C black smoker was imaged at the Beehive Site (Figure 1b) approximately 2 m from the main sulfide structure. Large numbers of swarming shrimp (*Rimicaris exoculata*) were observed in this area. On the dive preceding ALISS's deployment, a small beehive structure was knocked off the top of the chimney creating a vigorous black smoker. A portion of the chimney was removed revealing an approximately 1 × 2 inch central conduit lined with chalcopyrite. The ambient image shows light extending from the single orifice to ~10 cm above the orifice. As at the Logatchev vent, intensity increases with wavelength until attenuation becomes dominant around 947 nm. Emission in the center tile (705 nm channel) appears to be greater at Logatchev than at Snake Pit. This may be due to Snake Pit's lower temperature, or a difference in non-thermal

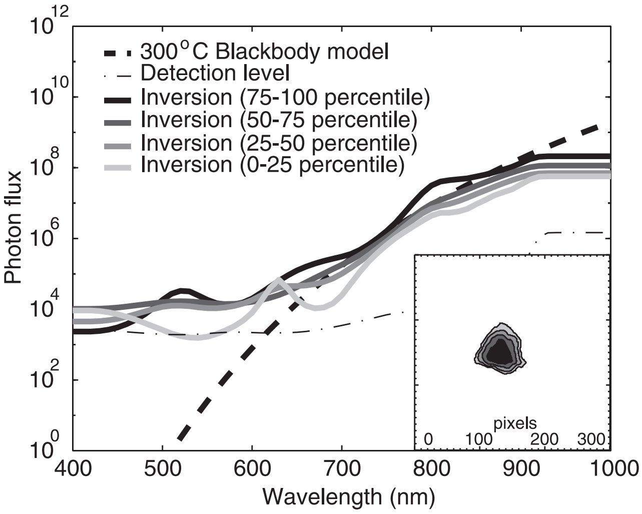

Figure 2. Inversion spectra for photon flux (photons/cm^2/sec/sr) from different quartiles of the source area at the middle smoker from Lucky Strike vent. Photon flux at the orifice (75–100 percentile region) corresponds well to a 300°C blackbody of emissivity 0.3. Excess light (over thermal radiation) is observed in the visible region, and around 800 nm. The inset shows the source region for each quartile (compare to Figure 1c).

sources. It is important to keep in mind that while some channels may appear to have no emission, computer processing of the image can reveal low light levels and slight intensity variations that are imperceptible to the eye.

[11] Lucky Strike Hydrothermal Field is located atop the Lucky Strike Seamount [*Langmuir et al.*, 1997] and is much shallower (~1694 m) than the previous two sites. The vent imaged by ALISS had an orifice temperature of 318°C. Figure 1c shows the ambient light image which contains three distinct vent orifices. Due to its lower temperature, the intensity from this vent is lower than the previous two vents. However, it exhibits the same characteristic increase with wavelength due to thermal radiation. The center orifice was isolated and was processed with the inversion routine discussed in *White et al.* [2002]. The inversion spectra are shown in Figure 2. Long wavelength emission from the highest intensity quartile corresponds well to a 300°C blackbody with an emissivity of 0.3. Previous studies of vent light have shown that black smokers have an emissivity of ~0.3, and that the temperature of the fluid as it exits the orifice is approximately 20°C less than the internal orifice temperature measured by the *Alvin* temperature probe [*White et al.*, 2002; *White et al.*, 2000]. In addition to the thermal radiation observed at long wavelengths (>700 nm), significant non-thermal radiation is observed at shorter wavelengths. The highest quartile shows a peak at 500–550 nm that is on the order of 10^4 photons/cm^2/sec/sr. As one moves away from the orifice, this peak decreases while a new peaks at 600–650 nm and 400–450 nm appear.

[12] The excess emission observed at Lucky Strike in the visible region of the spectrum is similar to some of the Pacific vents. Comparisons with data from black smokers and a beehive structure on the EPR suggest that the emission at 500–550 is due to a mechanism related to the sulfide structure, such as crystalloluminescence. This emission peak is observed in the spectra from the surface of a beehive structure and from black smokers on the sides of sulfide structures [*White et al.*, 2002]. The peak at 600–650 nm was only previously observed from the fluid emanating from a beehive, and was thus thought to be due to a fluid-related mechanism such as chemiluminescence. Failure to observe this peak at other black smokers where chemiluminescence should also be occurring could be due to the fact that at higher temperature vents this peak is masked by the higher thermal radiation present. It is not clear whether the overall broadband emission observed in the visible region is due to a combination of sources, or a single source such as vapor bubble luminescence (which appears to be wavelength independent in the 380–600 nm region [*Chakravarty and Walton*, 2001]).

[13] A series of 30-second exposures was also obtained from the Lucky Strike vent. The time series for each filter (normalized by the mean) is shown in Figure 3. A similar time-series from Puffer Vent on the Juan de Fuca Ridge showed a large shift in emission in the visible region, while the longer wavelengths remained relatively constant [*White et al.*, 2000]. The time-series from Lucky Strike (which spanned 5 minutes) also shows stable long-wavelength emission and significant time-variation in the emission below 700 nm. The standard deviation of the 753, 792, and 870 nm channels is an order of magnitude lower than that for the shortest wavelengths after normalizing by the mean flux. The variation in the 450 and 652 nm channels is due to camera noise, as the mean flux is essentially zero over this time period. The similarity in trends of the 550 and 599 nm channels, however, suggest that we are observing real variation in light emission. This time variability, in addition to the emission levels observed in the visible region indicate that non-thermal light emission is occurring at these vents.

4. Conclusions

[14] ALISS data from vents on the MAR show that while there is a variation in light emission between deep-sea vents, the differences between the North Atlantic and Eastern Pacific are not large nor are they related to ambient pressure

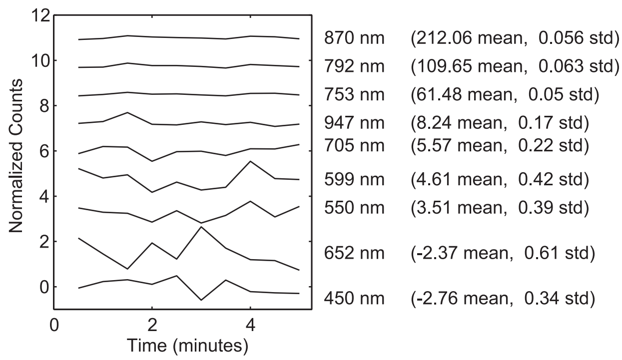

Figure 3. Light emission (30 second exposures) observed at the 318°C Lucky Strike vent over a 5 minute period. Data are normalized by the mean flux per band and offset for ease of viewing. All filters are 100 nm nominal bandwidth. The mean flux and standard deviation (after normalization) are given for each channel. The longer wavelengths are fairly constant over time, while the shorter wavelengths show high variability.

differences. The vents imaged on the MAR were both deeper (>3000 m) and shallower (<2000 m) than those previously imaged in the eastern Pacific (~2200–2500m). It may be hypothesized that differences in pressure will significantly affect some of the non-thermal source mechanisms (particularly since these pressures lie on opposite sides of the critical point of water [*Bischoff and Pitzer*, 1985]). However, the present data suggest that pressure does not significantly affect light emission from vents. Instead, variation is seen at individual vents and appears to be due to local properties such as temperature, chemistry, or mineralogy.

[15] All vents emit thermal radiation in the far-red and near-infrared due to the temperature of the exiting fluids, and most vents, both in the Pacific and the Atlantic, also emit time-varying, non-thermal radiation in the visible region of the spectrum [see also *White et al.*, 2000]. This non-thermal light is consistent with emission through mechanisms such as chemiluminescence, crystallo- and triboluminescence, and vapor bubble luminescence [see *White et al.*, 2002 for a detailed discussion of possible sources]. However, the extent to which these various mechanisms contribute to vent light cannot yet be discerned. Higher resolution data from vents, and a greater understanding of light emission mechanisms and their spectra are needed to determine the contribution of these sources to vent light.

[16] The confinement of the vent shrimp *Rimicaris exoculata* to the MAR has led to speculation that vent light in the Atlantic may be stronger in the visible (particularly around 500 nm where *R. exoculata* is most sensitive). While visible light was observed at vents on the MAR (including a small peak at 500–550 nm), this light was not significantly greater in magnitude than the visible light observed at vents in the Pacific. This suggests that ambient light conditions are not responsible for the exclusion of *R. exoculata* from the Eastern Pacific.

[17] Questions also remain regarding why there is a 500 nm absorption maximum of *R. exoculata* and whether there is a second absorption maximum in the 800 to 1000 nm band (data from *Van Dover et al.* [1989] extend only to 800 nm). *Pelli and Chamberlain* [1989] suggested that *R. exoculata* could "see" light from a 350°C blackbody. If this is the case, the existence of excess emission in the visible (where *R. exoculata*'s absorption peaks and where attenuation is at a minimum) makes it more likely that the shrimp can detect vents from their light emission. However, *Renninger et al.* [1995] showed that *R. exoculata* has strong chemical sensitivity which allows it to locate hydrothermal vents, indicating that visual cues are unnecessary. The only way to determine if *R. exoculata* can actually "see" vents, and to understand how they use that information is through behavioral studies of the shrimp at vents or in the vicinity of light sources which mimic vent light.

[18] **Acknowledgments.** The authors wish to thank the Captain and crew of the R/V *Atlantis* and the *Alvin* Group for their skill in deploying the ALISS camera; John Bailey and Rod Catanach for technical assistance; Tony Tyson and Alan Walton for helpful discussions. This paper has benefited from the comments of the editor and two anonymous reviewers. Field observations were collected during an *Alvin* dive series supported by NSF Biological Oceanography grants to CLVD (OCE 98-18550, 99-10161, 99-82999) and from NASA's Astrobiology and Exobiology Programs. GTR was supported by ONR grant N00014-00-1-0010.

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