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Variations in ambient light emission from black smokers and flange pools on the Juan de Fuca Ridge

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Abstract. Ambient light emitted by high-temperature black smokers and flange pools on the Juan de Fuca Ridge was imaged using a new spectral imaging camera. Most of the light is emitted at long wavelengths (700-1000 nm) and corresponds well to thermal radiation from a body at the same temperature as the vents/flanges. However, black smokers also emit time-varying radiation in the visible region (400–650 nm) which cannot be explained by a thermal source. This visible radiation is 1–2 orders of magnitude greater than would be expected for purely thermal radiation; it exhibits variation with time, despite relatively constant vent temperatures; and it is not associated with the hottest part of the plume (i.e. the orifice). Flange pools do not exhibit excess visible light over that for a thermal source, suggesting that the light at smokers is caused by mechanisms related to turbulence, mixing, or precipitation.

Introduction

The search for ambient light at hydrothermal vents was prompted by the discovery of the vent shrimp *Rimicaris exoculata*. Although this species lacks normal shrimp eyes, it was found to have a novel photoreceptor (Van Dover et al., 1989) uniquely designed to detect very low levels of light (O'Neill et al., 1995). Initially, it was proposed that high-temperature vents were hot enough to emit thermal (black body) radiation that could be detected by the shrimp (Pelli and Chamberlain, 1989). In 1988 on an *Alvin* dive to the Juan de Fuca Ridge, ambient vent light was first imaged using a CCD (charge coupled device) camera, thus verifying its existence (Smith and Delaney, 1989; Van Dover et al., 1988).

Early measurements at black smokers on the East Pacific Rise and the Mid-Atlantic Ridge obtained with a simple photometer verified that long wavelength (>700 nm) light, consistent with thermal radiation, was emitted at vents. These measurements also suggested that a component of non-thermal light existed in the 400–700 nm range. This light appeared to vary with time, and was much greater than predicted by thermal radiation alone (Van Dover et al., 1996; White et al., 1996). However, the photometer was only capable of observing up to four wavelength bands simultaneously, and was unable to image the vents and hence constrain the source region. To understand what sources may contribute to light emission at hydrothermal vents, better characterization of the light and its temporal and spatial variations was needed.

A specially designed CCD camera called ALISS (Ambient Light Imaging and Spectral System) was built to simultaneously image vent light in nine wavelength bands. CCDs have the advantage of being small, low-power, linear devices that are inherently integrating (i.e. long exposures can be used to build up signal from faint objects). Thus, they are ideal for low-light level imaging on the sea floor. ALISS contains a set of optics which divides the CCD plane into nine sections. A set of nine lenses, each covered with a different optical bandpass filter, project the same object onto each section. ALISS contains two filter arrays such that eighteen wavelength bands (spanning the 400–1000 nm region) can be observed on each dive. This provides both spatial and spectral information. By taking a number of images through time, temporal information is also obtained.

This paper focuses on the differences between ambient light from black smokers and flange pools on the Juan de Fuca Ridge. The high-temperature, relatively stable fluids pooled beneath flanges appear to emit purely thermal radiation. However, black smoker fluids, which are turbulent and undergo rapid mixing with ambient seawater resulting in chemical precipitates, emit a non-thermal component as well. This component, which is dominant in the visible region of the spectrum, is time-varying and is more prominent away from the orifice. A number of mechanisms could be solely, or jointly responsible for this type of emission.

Geological Setting

ALISS images of both black smoker vents and flange pools in the Main Endeavour Field of the Juan de Fuca Ridge were obtained during a 1998 *Alvin* cruise. The Main Endeavour Field is located along the western wall of the rift valley at 47°57' N, 129°06' W and a depth of 2220–2200 m (Crane et al., 1985; Tivey and Delaney, 1986), and contains a number of large (20 x 25 x 20 m) sulfide structures (Delaney et al., 1992).

The advantage of working in this area is the presence of both focused, high-temperature black smoker vents and pools of high-temperature fluids trapped beneath sulfide-sulfate-silica flanges (Delaney et al., 1992). Thus, we were able to image the light from hot, relatively stable fluid in a flange pool to compare with light from hot, turbulent black smoker fluid which is rapidly mixing with ambient seawater.

Data will be presented from three vents to show how light from smokers and flanges differ. Puffer vent is so named because it appears to "puff" due to boiling. The chemistry, along with temperature and pressure conditions, indicates subcritical phase separation at or just below the seafloor

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(Butterfield et al., 1994). The *Alvin* temperature probe recorded a high temperature of 372° C deep inside the orifice, and ~330° C just outside the orifice. Sully vent also appeared to be boiling and had an orifice temperature of 371° C. Lobo flange had a surface area of ~0.8 m^2 at a temperature of 332° C.

Operations & Data Processing

ALISS is deployed from the submersible *Alvin*. The camera is mounted on a frame in the *Alvin* science basket that allows it to be tilted, raised and lowered, and panned left and right. ALISS is positioned 50 cm from the vent of interest (as measured using ranging lasers) and has a field of view of 16x16 cm. A number of five-minute exposures are taken with each filter array at each vent. At Sully vent, a set of sixty 30-second exposures was taken with a single filter array to study temporal variation over a 30 minute period. During imaging, *Alvin's* lights are secured, viewports are blacked out, and the submarine must be stable.

The ALISS images were processed using the IRAF (Image Reduction and Analysis Facility) and IDL (Interactive Data Language) image processing packages. A number of corrections must be made to remove bias level, bias structure, dark charge, and to correct for pixel-to-pixel variations (Tyson, 1986). The bias level, bias structure, and dark charge are subtracted from each image. The pixel-to-pixel variation is corrected for by dividing the image by a flat field image — an image of an evenly illuminated surface scaled to a mean value of one. A number of five-minute exposures are made of each vent and, after performing the above corrections, they are median averaged to reduce noise. The signal in each band is summed and divided by exposure time to determine a count rate.

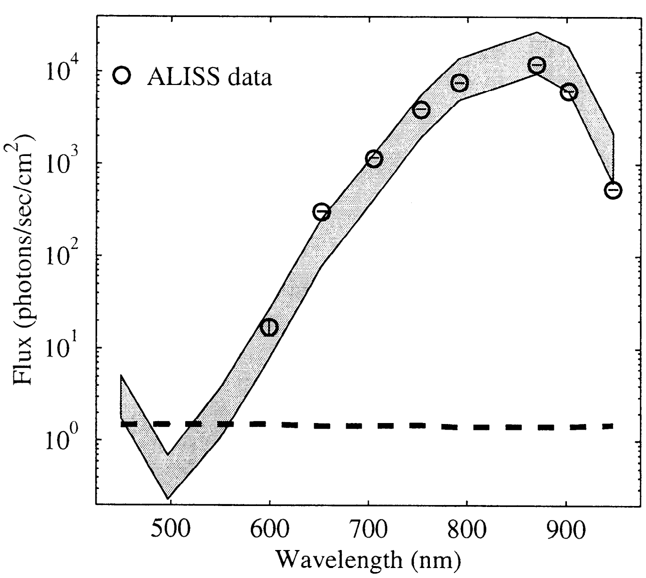

Figure 1. ALISS spectrum of Lobo flange (dive 3235). All data are from 100 nm nominal bandwidth filters. Black circles are the ALISS data with 2σ error bars. (Note that the error bars are equivalent to or less than the size of the symbols). The gray band indicates what ALISS would see through 50±5 cm of water and its filters (solid angle = 4.5×10^{-5} str) given a purely thermal source at 332±10° C with an emissivity of 0.9±0.1. (The higher expected flux through the 450 nm filter is due to a leak of long wavelength light). The dashed line indicates the effective detection level of the ALISS camera.

Calibration factors are applied to convert this signal into photon flux which can then be compared to the predicted flux of a theoretical black body. The camera was calibrated prior to the cruise using the Quantum Efficiency Test Machine of the Palomar Observatory Group at Caltech.

The ALISS data are subject to noise inherent in the camera system: (1) thermal noise associated with dark charge — this can be reduced by cooling the CCD, (2) photon noise associated with the signal — for a Poisson process this is the square root of the average signal, and (3) readout noise associated with the electronics. It is the combination of the dark noise and readout noise that determines the effective detection limit of the camera.

When comparing the light measured by ALISS to thermal radiation produced at the vents, one must consider both the attenuation through seawater; and the emissivity of the vent fluid — how similar it is to an ideal black body (emissivity = 1). Both of these factors are not well known in the vent environment and thus introduce some uncertainty. For our analysis we used a combination of attenuation data from Smith & Baker (1981) and Kou et al. (1993), which has been corrected for temperature effects as described by Pegau et al. (1997). Emissivity is more difficult to constrain. Since the temperature and emitting area of the vent are approximately known, emissivity is the only unknown factor in the black body equation. Thus, an emissivity value was chosen that produced the best fit with the ALISS data at long wavelengths (where thermal radiation is believed to be dominant).

Ambient Light Emission

The light emission spectra from a flange pool and a black smoker are shown in Figures 1 and 2, respectively. These figures show the light flux from a source of unit area at a distance of 50 cm (the focal distance of the ALISS camera) as seen through eleven ~100 nm bandwidth filters. The light that leaves the vent is attenuated by traveling through 50 cm of ~2° C seawater. Attenuation is an exponential function of distance, and the attenuation coefficient varies with wavelength — from ~2×10^{-4} cm^{-1} at 400 nm to ~3×10^{-1} cm^{-1} at 1000 nm. Thus, although thermal radiation from a ~330° C body increases with wavelength to a peak at ~4600 nm, the high attenuation in seawater causes the transmitted intensity of long wavelength light (>870 nm) to drop off. The data from ALISS are compared to calculated thermal radiation for a body at the same temperature as the vent/flange. Emissivity is estimated by fitting the data at long wavelengths as described in the previous section. The thermal radiation is attenuated through 50 cm of seawater and convolved with the ALISS filter curves for direct comparison with the ALISS data. The band of expected flux from black body theory reflects uncertainties due to emissivity (±0.1), actual distance (±5 cm), and actual temperature (±10° C).

The data from Lobo flange (Figure 1) show excellent agreement with the black body model. Emission increases with wavelength from 600 nm to a peak at 870 nm and then falls off due to seawater attenuation. Light shorter than 600 nm in wavelength was below the detection limit of the camera. The temperature of the flange pool was accurately measured to be 332° C with the *Alvin* temperature probe. Using this value, an emissivity of ~0.9 is required to fit the data.

Emission from Puffer vent is shown in Figure 2. ALISS images of the vent show that light emission is highest at the

Table 1. Calculated Photon Flux (photons/cm^2/sec) for a 330° C Black Smoker/Flange

Wavelength (nm)	Black Smoker (emissivity = 0.3) at orifice[a]	Black Smoker (emissivity = 0.3) 10 cm away[b]	Flange Pool (emissivity = 0.9) at orifice[c]	Flange Pool (emissivity = 0.9) 10 cm away[c]
700–800	2.77×10^8	6.82×10^6	1.65×10^9	1.28×10^9
800–900	6.16×10^9	1.23×10^8	3.69×10^{10}	2.31×10^{10}
900–1000	7.04×10^{10}	2.17×10^8	4.14×10^{11}	4.08×10^{10}

[a]solid angle = π steradians (quarter-space)
[b]solid angle = 0.1 steradians (10 cm^2 source at 10 cm)
[c]solid angle = 2π steradians (half-space)

orifice where the temperature is the highest, and decreases with distance up the plume. Figure 2 shows the spectra of light between 0–2 cm, 2–2.5 cm, 2.5–3 cm, and 3–3.5 cm up the plume (all extracted from the same image). The light at longer wavelengths (600–1000 nm) corresponds well to thermal radiation from a 330° C body with an emissivity of 0.3. As one moves up the plume, the temperature drops off, as does the light emission at long wavelengths. What is interesting is that, unlike at flanges, ALISS is able to detect light at the shorter wavelengths (400–600 nm). In fact, at 2–2.5 cm above the orifice, a significant amount of light is seen by the 500 and 550 nm filters. As an equivalent amount of light is not seen by the 450 and 600 nm filters, and all of these filters are 100 nm in bandwidth, the excess emission is limited to the 500–550 nm range. Emission of this magnitude at this distance from the vent orifice cannot be explained by thermal radiation.

The time series data from Sully vent also exhibit interesting behavior. Sixty 30-second images were obtained over a 30 minute period. Figure 3 shows the light emission through time. The longer wavelengths show a relatively constant emission over time with a slight periodic variation (most likely caused by pulses in the plume due to boiling). However, the shortest wavelengths (450, 550, and 600 nm) show a large jump in emission (on the order of ~1.8×10^5 photons/sec) at 15 minutes. Since this shift is not seen at the longer wavelengths, movement of the submarine or a change in temperature are not possible causes.

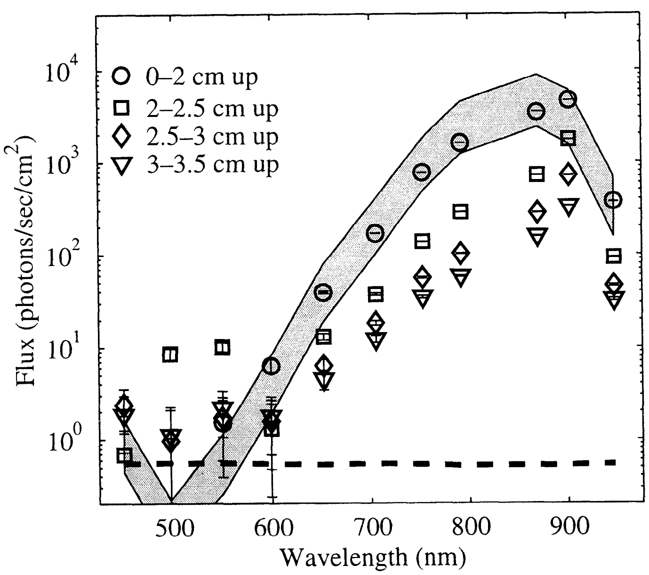

Figure 2. ALISS spectrum of Puffer vent (dive 3234). All data are from 100 nm nominal bandwidth filters. ALISS data with 2σ error bars are indicated by black circles (0–2 cm above the orifice), squares (2–2.5 cm up), diamonds (2.5–3 cm up), and triangles (3–3.5 cm up). The gray band indicates what ALISS would see through 50±5 cm of water and its filters (solid angle = 4.5×10^{-5} str) given a purely thermal source at 330±10° C with an emissivity of 0.3±0.1. (The higher expected flux through the 450 nm filter is due to a leak of long wavelength light). The dashed line indicates the effective detection level of the ALISS camera.

Discussion

Our investigations show that light is ubiquitous at high-temperature hydrothermal vents. Light emission is highest at long wavelengths (>700 nm) at both black smokers and flange pools. This long wavelength light fits the expected flux of a black body suggesting that the dominant source of this light is thermal radiation from the high-temperature vent fluids. Flange pools, backed by hot opaque rock, have a higher emissivity — and consequently a higher intensity — than the radiating semi-transparent fluid of a black smoker. In addition to thermal radiation, black smokers emit a time-varying, visible component of light that cannot be explained by a thermal source.

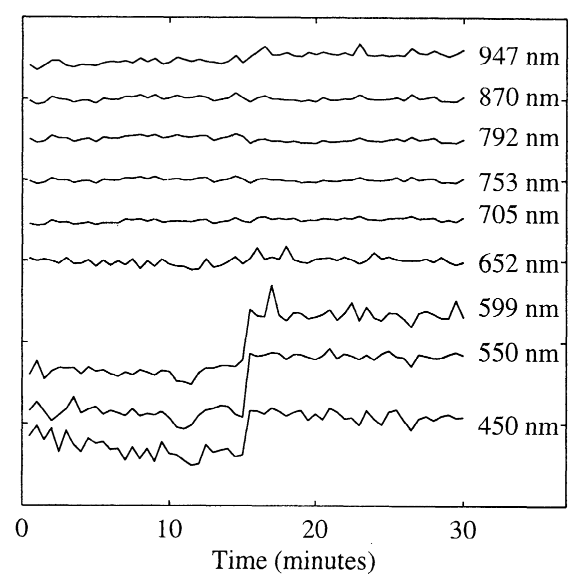

Figure 3. Light emission observed at Sully vent (dive 3238) over a 30 minute period. Data are normalized by the mean flux per band and offset for ease of viewing. The shift in 450, 550, and 599 nm bands at 15 minutes is on the order of 1.8×10^5 photons/sec. All filters are 100 nm nominal bandwidth.

The fact that visible light is present at black smokers and not flange pools suggests that it is caused by some mechanism related to turbulence, mixing, or precipitation. A number of possible sources are discussed by Reynolds (1995) and LITE Workshop Participants (1993). Some of the more likely mechanisms are: (1) sonoluminescence (SL) — light emission from the implosion of small bubbles; (2) crystallo- and tribo-luminescence (XTL and TL) — light emission due to the crystallization and fracturing of minerals, respectively; and (3) chemiluminescence (CL) — light due to chemical reactions.

The occurrence of boiling suggests the possibility of bubble formation which could lead to sonoluminescence. However, Becker et al. (1992) found that the SL spectrum of seawater is dominated by a large peak at 589 nm (due to excited-state sodium) which is not observed in our data. Minerals formed in hydrothermal vent plumes are known to be XTL and TL active. Nelson (1926) and Walton (1977) show TL light emission from ZnS (with metal impurities) between 450 and 650 nm. Thus, minerals formed in the plume may emit visible radiation during crystallization or fracturing due to thermal shock. Recent work by Tapley et al. (1999) suggests that sulfide oxidation at vents produces chemiluminescence. The mixing of sulfide-rich fluids with oxygenated seawater appears to emit light in the visible region of the spectrum. Most of these sources are not yet fully understood and their spectra not well characterized. However, they are known to generate visible light, and require conditions that are consistent with hydrothermal vent systems.

The existence of light at hydrothermal vents leads to the question of whether there is sufficient light for photo-biochemical processes. Table 1 shows calculated photon flux per unit source area per second from smokers and flanges at distances of zero and 10 cm from the orifice. Flanges, in particular, may provide a possible environment for photosynthetic bacteria. Flanges provide a large area (on the order of 1 m^2) of light emission and a steady environment, unlike black smoker orifices, which offer a small surface area for microbial growth within the zone of illumination (a few cm^2) and which have structural features that may change rapidly. Overmann et al. (1992) described a phototrophic sulfur bacterium from the Black Sea capable of thriving at low-light levels (on the order of 10^{11} photon/cm^2/sec). In fact, long-wavelength light from hydrothermal vents approaches this threshold. Approximately 4.14×10^{11} photons/cm^2/sec would be observed in the 900–1000 nm band by an organism at a flange pool, but this flux decreases by an order of magnitude at a distance of 10 cm from the flange due to seawater attenuation. Photosynthetic bacteria with bacterio-chlorophyll absorption maxima at 867 nm have been isolated from two water samples collected 10's of meters above the Juan de Fuca vent field (Yurkov and Beatty, 1998), but a systematic survey for bacterial phototrophs at vents and demonstration of geothermally-driven photosynthesis remain to be conducted.

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