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Light at deep-sea hydrothermal vents

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Abstract. Ambient light spectral data were acquired at two deep-sea hydrothermal vents with a temperature of ~350°C: the Hole-to-Hell site on the East Pacific Rise at 9°N and the Snake-Pit site on the Mid-Atlantic Ridge. Measurements were made with a simple, multi-channel photometer which simultaneously detected light in four 100 nm-wide bands over the wavelength range of 650-1050 nm. Most of the light detected is near-infrared (750-1050 nm), but there is a 19x greater photon flux than expected from thermal radiation alone at shorter wavelengths (650-750 nm) at the Hole-to-Hell vent. At Snake Pit, more light in the 750-850 nm band was observed 10 cm above the orifice where the temperature was 50-100°C than at the 351°C vent opening. These data suggest the presence of non-thermal light sources in the vent environment. Some possible non-thermal mechanisms are identified, but further data will be required to resolve them.

Introduction

The idea that deep-sea hydrothermal vent environments might represent non-solar photic habitats arose from observations of a novel photoreceptor in shrimp (*Rimicaris exoculata*) that swarm over surfaces of black smoker chimneys emitting high temperature (350°C) fluids on the Mid-Atlantic Ridge (Van Dover et al., 1989). These shrimp, originally described as eyeless, in fact have an expanded eye. Instead of being located at the ends of eyestalks, the eyes are positioned beneath the antero-dorsal portion of the cephalothorax, immediately beneath a thin, transparent carapace. Anatomical details indicate that the paired eyes connect to the brain at the optic lobes and that they are derived from normal shrimp eyes. Image-forming optics are not present, and the entrance aperture, volume of photoreactive membrane (retina), and concentration of photoreactive pigment (rhodopsin) in *R. exoculata* are several times greater than is encountered in typical shallow-water shrimp species (O'Neill et al., 1995; Van Dover et al., 1989). The photopigment absorbs maximally at ~500 nm, suggesting that this is the wavelength of the stimulating light source (Van Dover et al., 1989; Pelli and Chamberlain, 1989). Attributes of this photoreceptive organ support the hypothesis that it is adapted for detection of a very dim source of light.

The most obvious source of light at high temperature vents is thermal radiation from the emitted hydrothermal fluids (Van Dover et al., 1989; Pelli and Chamberlain, 1989). The spectrum of a perfect 350°C blackbody peaks in the mid-to-far infrared, but the tail of the spectrum extends into the visible. The intrinsic attenuation of light in seawater limits significant light transmission to the 400 to 1050 nm band.

Digital images at a high temperature vent (Endeavour Hydrothermal Field, Juan de Fuca Ridge) taken by a CCD digital camera demonstrate that light is indeed associated with high temperature fluids as they exit the vent orifice and mix with seawater (Van Dover et al., 1988; see figures in Van Dover et al., 1994). With the addition of bandpass filters to the camera, the calculated flux at 750-850 nm (corrected for the attributes of the camera system, the absorption of light in seawater, and assuming an emissivity of 0.3) was 7.7 x 10^{10} photons cm^{-2} s^{-1} (J.A. Tyson, in LITE Workshop Participants, 1993). While crude, these first direct observations of vent light appeared to be consistent with the light flux emitted by a 350°C source, but uncertainties about the emissivity characteristics of hydrothermal fluids and the spectral absorption of seawater in the vent environment placed large uncertainties (50-100%) on the calculation. Furthermore, the digital images do not prove that thermal radiation is the sole source of the light and other mechanisms may be superimposed (Van Dover et al., 1994).

In this paper, more precise photometric data are presented which suggest that thermal radiation alone cannot account for the light observed at deep sea black smokers. In particular, a substantial excess of light over that predicted by a thermal mechanism is observed in the near infrared at a vent on the East Pacific Rise. On the Mid-Atlantic Ridge, more infrared light was observed 10 cm above the vent, where the ambient temperature had dropped below 100°C, than at the 351°C orifice. Further data will be required to discriminate among possible non-thermal emission mechanisms.

Methods

A new instrument, called Optical Properties Underwater Sensor or OPUS, was constructed to further quantify vent light. OPUS consists of a 4-photodiode (Hamamatsu S2386-8K, 33 mm^2 active area) array housed in a 10 cm diameter lucite pressure case with a 7.6 cm thick lucite optical window. Infrared-blocked interference bandpass filters (100 nm bandwidths centered at 700, 800, 900 and 1000 nm) were fixed in front of the photodiodes. Photodiode output was passed through current and voltage amplifiers with a nominal transfer function of 8 x 10^9 V/(W-cm^{-2}). Data were recorded on an internal Tattletale data logger.

OPUS was deployed by the submersible *Alvin*. The optical window of the instrument was positioned 10 cm from the orifice of a vent. All external lights on the submersible were extinguished and viewports were blacked-out during each data collection event of up to 30 s duration. Background counts, collected *in situ* within meters of the sampling sites, were negligible. OPUS was used in 1993 to collect quantitative spectral data on ambient light at Snake Pit (3600 m; 23°22'N, 44°57'W) and at Hole-to-Hell (2500 m; 9°50'N, 104°17.5'W). The maximum, stable temperature measured at both vent orifices was 350-351°C. At Snake-Pit, data were obtained from only one of the four channels (750-850 nm; sampling rate = 5 Hz). Data were collected with all four channels at the Hole-to-Hell site. For each wavelength band, the mean photon flux over 11 s records

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Table 1. Calculated Flux for a 350°C Black Body Source

Wavelength (nm)	photons $cm^{-2}s^{-1}sr^{-1}$	photons $cm^{-2}s^{-1}$ at 10 cm
650-750	1.70×10^{7}	1.67×10^{4}
750-850	4.95×10^{8}	4.87×10^{5}
850-950	6.75×10^{9}	6.64×10^{6}
950-1050	5.36×10^{10}	5.27×10^{7}

(sampling rate = 20 Hz) was computed and used in subsequent calculations. The standard deviation was 13% of the mean value for the 750-850 nm channel and less than 10% for the other three channels. OPUS was calibrated after the second (Hole-to-Hell) cruise at the Harvard Smithsonian Astrophysics Laboratory to an NBS-traceable standard light source.

The OPUS data were analyzed in a number of ways. Initial data reduction includes correction for the measured detector dark current at *in situ* temperature and the application of channel-specific calibration factors. The transformation of the photon flux at OPUS to that at the source requires further corrections for optical absorption in seawater, optical absorption by the lucite window, and the optical throughput of the filters and diodes. All of these quantities were measured with the exception of attenuation in seawater. The absorption of light in seawater is markedly wavelength dependent. Literature values are fairly consistent for $400 < \lambda < 900$ nm, but from 900-1050 nm there are large variations in the reported attenuation. We use a consensus curve developed by Reynolds (1995) based on data from Curcio and Petty (1951) and Wolff and Zissis (1989). Since scattering in the vent environment is probably significant, this curve should be regarded as a lower limit. The reverse procedure to transform the theoretical photon flux at a source to that which OPUS would observe requires similar corrections.

Calculation of the absolute photon flux from a thermal source radiating into seawater must account for the index of refraction of seawater (n=1.325), and include the size of the emitting region and the emissivity of the source. While the size of the emitter may be roughly estimated from vent images, the emissivity of vent fluids is poorly determined. However, comparison of ratios of photon fluxes over different wavelength bands with those expected for a blackbody source provides a robust test for the presence of non-thermal light emission mechanisms. This may be predicted without knowledge of the emissivity (assuming it is not wavelength-dependent) and the size of the emitting region.

Results and Discussion

Table 1 gives predicted values for the photon flux per unit time per unit solid angle at the source and for an OPUS-size target at 10 cm (which subtends a solid angle of 0.984×10^{-3} sr in seawater) computed directly from Planck's equation for a 350°C black body. For the calculation, the product of the source area and emissivity was assumed to be 1, corresponding to a 3 cm^2 source consistent with vent images and an emissivity of 0.3. This value should be regarded as an upper limit, in large part because the attenuation correction cannot account for scattering which is probably substantial in the vent environment.

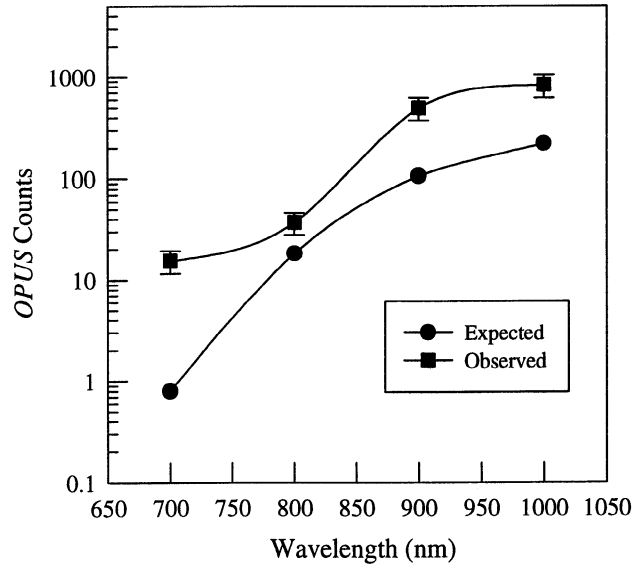

Figure 1. Expected OPUS counts at the Hole-to-Hell vent based on thermal radiation from a 350°C source (with an area-emissivity product of one after correction for geometry of the source and receiver and the wavelength-dependent attenuation of the signal through seawater) is compared to observed OPUS counts with 25% error bars. Points plotted represent integrated values across 100 nm bandwidths centered at 700, 800, 900 and 1000 nm, respectively.

Table 2. Expected and Observed OPUS Counts

Wavelength (nm)	Expected	Observed	Obs/Expected
650-750	0.8	15.3	19.1
750-850	18	36.9	2.0
850-950	106	497	4.7
950-1050	220	825	3.8

Table 2 and Figure 1 compare the predicted photon flux (from Table 1 after transformation to OPUS counts using the measured channel calibration factors) with observed OPUS counts at the Hole-to-Hell site. The uncertainty on the measured values is hard to quantify, but is believed to be about 25%. Excess light over that from thermal radiation was observed for each of the four wavelength bands. The observed excess is not uniformly distributed over wavelength, and is maximal (19x the expected value) at 650-750 nm. Furthermore, the comparison of expected and observed ratios of photon flux integrated over 100 nm bandwidths (Table 3) clearly demonstrates that the spectrum of the light source at the orifice of this black smoker does not conform with that of a blackbody with a wavelength-independent emissivity in the 650-750 nm band. We thus conclude that thermal radiation cannot be the sole source of light at this vent.

Further evidence for a non-thermal source of radiation at hydrothermal vents comes from OPUS observations at a 351°C black smoker chimney at Snake Pit, where bursts of 750-850 nm light were detected in a region of 50-100°C mixed hydrothermal fluids and seawater approximately 10 cm above the orifice during a 40 s recording interval (Figure 2). No 750-850 nm light was detected at the orifice in a sequential set of observations. If thermal radiation were the sole source of light 10 cm above the orifice, then the photon flux should be diminished by more than 10 orders of magnitude relative to that at the orifice, and would be temporally continuous rather than episodic. Light with these temporal and spatial characteristics was not observed at the Hole-to-Hell site, suggesting that light properties of black smokers may be site-dependent.

Table 3. Ratios of Photon Flux by Wavelength Band

	800/700	900/700	1000/700	900/800	1000/800	1000/900
Expected at source	29	397	3153	13.6	108	7.9
Expected at 10 cm	23	138	287	5.9	12.3	2.1
Observed at 10 cm	2.4	32.5	54	13.5	22.4	1.7

The conclusion that thermal radiation is not the sole source of light at vents raises the obvious issues of what additional mechanisms might account for the observations at Hole-to-Hell and Snake Pit and how these sources might vary between sites. Bioluminescence seems unlikely to be important given the extreme temperature at the emitting region and the presence of a light excess at wavelengths longer than 650 nm rather than in the blue-green region typically emitted by bioluminescent organisms. More plausible light sources include crystallo-, tribo-, sono- and chemi-luminescence. These sources of light typically have broad band (rather than line) emission spectra that lie within the 450 nm to 800 nm interval where we have observed a flux much greater than expected from thermal radiation. Crystalloluminescence is the emission of light that occurs at the onset of crystallization (Zink and Chandra, 1982). The descriptive term black smoker refers to the metal (Fe, Cu, Zn) sulfide crystals that precipitate as clear hydrothermal fluids mix with seawater. Crystalloluminescence spectra from metal sulfides have not yet been obtained, but an empirical correlation between photoluminescence and crystalloluminescence has been established, and metal sulfides are photoluminescentally-active at about 700 nm (J. Zink, private communication). Triboluminescence, where light is emitted when a crystal is stressed by mechanical means or thermal shock, is also a potential source of light (Walton, 1977; Zink, 1981). Black smoker minerals are known to be triboluminescentally-active (Walton 1977). If multiphase hydrothermal fluids exist, gas bubbles may be excited to oscillate and implode under conditions of turbulent flow, generating sonoluminescence with broad band radiation centered on the emission line of one of the alkali metal ions (Becker et al., 1992). Another possible mechanism is chemiluminescence which produces broad spectral bands in the visible part of the spectrum due to the direct conversion of chemical energy in organic compounds to light. Other sources of light at vents, including burning of methane in supercritical fluids and light from ionizing radiation, have been proposed. Additional details and analysis of possible light-generating mechanisms at vents are provided in Van Dover et al. (1994) and Reynolds (1995).

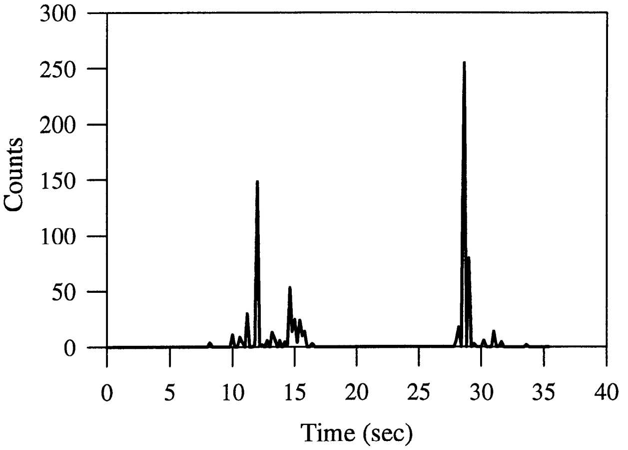

Figure 2. Counts observed during an OPUS deployment at the Beehive Mound (Black Smoker "G", Snake-Pit) on the 800 nm channel (750-850 nm) at a distance of 10 cm above the orifice. The ambient temperature at this height above the orifice was 50-100°C. No signal was detected on the 800 nm channel at the orifice (350°C).

To resolve these mechanisms, further measurements of the spectral character of light at black smoker vents are required, including observations at shorter wavelengths (450-650 nm) and better spatial and temporal resolution. Better characterization of the absorption properties of vent fluids is also necessary. The spectral study of light emitted by 350°C fluids in the absence of turbulence and precipitation would allow the separation of classes of emission that depend on turbulent flow (sonoluminescence), entrainment (bioluminescence) and precipitation (crystallo- and triboluminescence) mechanisms. Standing pools of 350°C hydrothermal fluids have been found beneath sulfide flanges (Delaney et al., 1992). Such regions where mixing with seawater and precipitation are minimized are among the priorities for future investigations of light at high temperature vents.

Calibration of OPUS to a standard light source and conservative corrections for absorption of light along the transmission path permit us to estimate the minimum photon flux emitted by the Hole-to-Hell black smoker and the photon flux reaching a 1 cm^2 surface at varying distances from the source (Table 4). Within 5 cm of the source, the minimum photon flux over wavelengths of 650-1050 nm is on the order of 10^{10} photons cm^{-2}s^{-1}. The maximum flux is more difficult to constrain given the uncertainty about some of the parameters, most notably attenuation by light scattering. It is possible to calculate a rough estimate of some larger than minimum flux by taking the minimum transmission character of the filters, a maximum attenuation of seawater, an estimate of attenuation due to turbidity (taken as 0.8) and the lowest possible sensitivities of the photodiodes. Using these assumptions, the photon flux reaching a point 5 cm from the Hole-to-Hell vent might be as much as 2 x 10^8 photons cm^{-2} s^{-1} in the wavelength interval 650-750 nm, and as much as 1.5 x 10^{11} photons cm^{-2} s^{-1} over 950-1050 nm.

We have confirmed here that light of non-thermal origin at vents exists and we have shown that this light is predominantly of long wavelength. The unusual modifications of the shrimp eye cited above may be one example of a biological adaptation to this light. While there may be sufficient light for vision by shrimp (Pelli and Chamberlain 1989), the role of the light in other photobiochemical processes is less clear but warrants further consideration. The minimum photon flux required for photosynthesis is on the order of 10^{11} photons cm^{-2}s^{-1} (Overmann et al. 1992), the same order of magnitude as the maximum calculation for the Hole-to-Hell vent. Bacterial phototaxis (motor response elicited by exposure to light) and photoheterotrophy (use of light energy to assimilate organic carbon) are other photobiochemical processes so far unexplored at vents. Nisbet et al. (1995) have proposed that light at deep-sea vents may have driven the evolution of photosynthesis through a sequence of phototaxis in response to infrared light followed by rudimentary photosynthesis using infrared light as a supplement to chemoautotrophy. There are thus several lines of inquiry regarding

Table 4. Minimum Photon Flux at Hole-to-Hell

	650-750 nm	750-850 nm	850-950 nm	950-1050 nm
photons $s^{-1}sr^{-1}$	1.9×10^{9}	5.1×10^{9}	9.8×10^{10}	1.9×10^{12}
photons $cm^{-2}s^{-1}$ at 5 cm	6.7×10^{7}	1.6×10^{8}	2.0×10^{9}	4.8×10^{9}
photons $cm^{-2}s^{-1}$ at 10 cm	6.7×10^{5}	6.4×10^{5}	1.6×10^{5}	1.1×10^{-2}

biological exploitation of this source of non-solar light energy that will benefit from further characterization of ambient light at vents.

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