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Kinematics of the high-excitation HH 890 jet in the Rosette Nebula *

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Abstract Photoionized jets immersed in HII regions display special properties, which made them a distinctive category of Herbig-Haro (HH) flows. Detailed studies of such jet systems became one of the key issues in our understanding of jet production and evolution. HH 890, initially called the Rosette HH2 jet, is the second photoionized jet discovered in the spectacular HII region of the Rosette Nebula. Contrary to conventional impressions of a jet, its discrete components are found to be unexpectedly broad and spatially detached from the proposed energy source. The jet displays additional unusual features which point to the disputable nature of the system. Here, we investigate the kinematics of the jet through high-quality echelle spectrograms. It is distinctively resolved into a fast component with a mean approaching velocity of –39 km s $^{-1}$ with respect to the systemic rest frame and a slow component with radial velocity centered at –9 km s $^{-1}$. The slow component indicates an apparently larger dispersion in radial velocity in various emission lines and is likely dissolving at roughly the speed of sound, which favors a photoevaporated origin. The [SII] doublet ratios indicate an electron density of $\sim$1.1$\times$10 ^{3} cm^{-3} in the collimated jet and $\sim$9$\times$10^{2} cm^{-3} in the HII region. This, along with the diffuse appearance of the extensive part of the jet, leads to a dissipation of the jet in the fully ionized medium of Rosette. In addition, time series of photometric observations provide evidence for remarkable light variations of the energy source. Its amplitudes of variation amount to $>$ 1 mag in both R and I, which is commensurate with the young evolutionary status of the source as indicated by a red, late type optical spectrum.

Key words: accretion disks — ISM: jets and outflows — stars: formation — stars: pre-main-sequence

1 INTRODUCTION

The recent discovery of an increasing number of collimated Herbig-Haro (HH) jets ejected by optically visible, young low-mass stars that are immersed in HII regions makes them a distinctive category of HH flows (Reipurth et al. 1998; Bally et al. 2000; Bally & Reipurth 2001; Li 2003; Li & Rector 2004). Detailed investigations of these so-called photoionized jets are of particular interest as they are associated with visible young stellar objects in their early stages of evolution. These jet driving sources would otherwise have been shielded by optically opaque envelopes and/or natal molecular clouds if they were not made visible by photoionization in the HII regions they reside in. On the other hand, the lifetime

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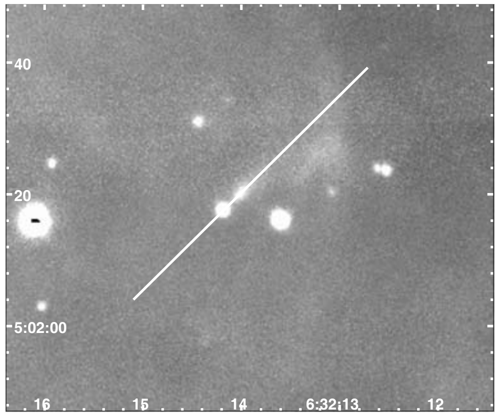

Fig. 1 Narrow-band imaging of the HH 890 jet in Hα taken by the KPNO 4m telescope. The slit orientation of our echelle spectroscopy is indicated by a straight line which was overplotted.

of such photoionizing jets can be short, which makes them hard to identify and even more crucial for studies of jet production and maintenance before these beams are lost in the glare of ionized nebulae.

Properties of externally ionized jets are found to heavily rely on local conditions of photoionization, i.e. the intensity of the UV radiation field. Some jet systems, such as HH 889 and HH 890 (please refer to *http://casa.colorado.edu/hhcat/*), formerly called the Rosette HH1 (Li & Rector 2004; Li et al. 2007) and HH2 (Li 2003), respectively, even contradict properties of conventional HH jets. The HH 890 jet, for example, is proposed by Li (2003) to be a monopolar jet with a high-state of ionization that originated from a late type star in the central cavity of the Rosette. In addition, the proposed jet shows an unusual appearance (Fig. 1); it is composed mainly of two discrete knots or jet components that resemble small nebulous entities. Furthermore, the more collimated part of the jet shows a detached appearance from both its energy source and the extensive portion of the jet. This jet system, which displays various anomalous features, if convincing, will be the only other case of a high-excitation jet that survived the harsh UV ionization of the Rosette Nebula. Numerous young stellar objects that originated from the same episode of star formation in this region could have already shed their envelopes and ceased mass ejection. The clues to the existence of any flows could also have been removed by external UV dissipation. The HH 889 and 890 jets, likely in the process of photo-dissipation, seem to be the last two relic jets still identifiable in the Rosette Nebula. Detailed studies of such jet systems may largely contribute to our understanding of external ionization of stellar jets, their maintenance and to the final theoretical solution of jet formation and evolution. There are, however, possibilities of solely spatial coincidence of high-excitation gas entities along the line of sight, rather than being manifestations of discrete ejecta from the proposed energy source as a result of episodic mass ejection and photoionization. This is a puzzling discovery that awaits further clarification by high quality observational studies. This study presents the kinematics of the proposed jet, which will definitely unveil its physical nature.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Echelle Spectroscopy

A single-order echelle spectrum of the jet system, covering both Hα and [NII] $\lambda\lambda$ 6548 and 6583, was obtained with the CTIO Blanco 4m telescope and its echelle spectrograph at the Ritchey-Critchien (RC) focus on 2005 January 12. With an exposure time of 1200 s, the spectrum was taken with the slit oriented along the jet direction at a position angle of 310° (see Fig. 1). The 79 l/mm grating and a Tek 2048 CCD were used, which resulted in a two-pixel resolution of 0.16 Å or a resolving power of $\sim$ 40 000 around Hα. The spectral data were reduced following standard procedures in the IRAF (Ver. 2.12) ECHELLE software package. This includes bias correction and gain-jump removal between the chips. Apparent cosmic ray impacts were manually rejected from the 2D spectrographs. The single-order data were then tilt removed and dispersion corrected. Wavelength calibration of the data was carried out based on Th-Ar lamp exposures and further improved by verifying the night sky emission lines, which resulted in an accuracy that was within 1 km s^{-1}. The spectrum was finally corrected to the heliocentric rest frame. A multi-order echellogram of the jet system was also achieved during this run of observations to estimate its electron density within the jet based on the [SII] $\lambda\lambda$6717, 6731 doublet.

2.2 Photometric Monitoring and Low-resolution Spectroscopy

We have initiated a photometric monitoring campaign to evaluate any possible variability of the jet driving source of HH 890. Differential photometric observations in R and I were carried out between 2004 December 31 and 2005 January 12, based on the Hsing-Hua 80 cm telescope that is located at the Xing-Long station of the National Astronomical Observatory of the Chinese Academy of Sciences (NAOC). Differential magnitudes of the jet source were obtained with corresponding routines in the NOAO IRAF package, taking two slightly brighter sources in the same field as comparison stars. Photometric variations between the reference stars in both bands are found to be within 0.04 mag throughout the monitoring campaign.

Low-resolution spectroscopy of the jet source with normal slit position was performed with the 2.16m telescope of NAOC from 2006 January 21 to 23. An OMR (Optomechanics Research Inc.) spectrograph at the RC focus and a PI Spec-10 CCD were used in this run of observations. A 200 Å mm^{-1} grating was used, which resulted in a two-pixel resolution of 8 Å. The spectral data were reduced with standard routines of IRAF in the conventional way.

3 KINEMATICS OF THE JET

As mentioned in the introduction, the proposed jet shows many unique features and it is necessary to clarify its physical nature. The high-quality echelle spectrograph taken along the jet direction, which covers both the Hα and [NII] emission lines, is shown in the upper panel of Figure 2. When the contrast of the spectrograph is adjusted, the Hα emission from the jet is found to be strong but shows a broad appearance. It is severely blended with the background nebular emission of Rosette. Fortunately, the [NII] emission lines at $\lambda\lambda$6548 and 6583 have low dispersion in velocity and are ideally resolved from emission from the receding shell of the HII region. Based on the well-resolved background emission in the counter jet direction, the collisionally excited [NII] emission lines from both the approaching and the receding shells of Rosette indicate distinct heliocentric radial velocities (V_{hel}) that are centered at 7 and 36 km s^{-1}, respectively. This yields a systematic expansion of 14 $\pm$ 1 km s^{-1} of the ionized gas and a systemic V_{hel} of 21$\pm$ 1 km s^{-1} in this part of the Rosette Nebula. It is noteworthy, however, that the forbidden [NII] emission from the receding shell of the nebula is much stronger, which hints at a larger emission measure on that side.

Both the Hα and [NII] emission from the jet indicate complex structures in the velocity field. We present the echelle spectrograph after careful background subtraction in the lower panel of Figure 2, in which nebular emission from the background HII region was almost completely removed. It is expected to represent only residual emission from the jet materials. Discrepant from the narrow-band imaging of the jet (Fig. 1), the residual emission from the discrete components appears as a continuous entity. This alone verifies that these components are most likely kinetically and physically related. More distinctive illustrations of the velocity structure of the jet traced by different emission lines are presented by the Position-Velocity plots in Figure 3.

The [NII] emission from the collimated part of the jet is, in a distinct manner, resolved into a high-velocity component (HVC) with a heliocentric RV centered at –18 km s^{-1} ($V_{sys} = -39$ km s^{-1}) and a low-velocity component (LVC) with a heliocentric RV of 12 km s^{-1} ($V_{sys} = -9$ km s^{-1}). This is crucial as the clear existence of the HVC elucidates the jet nature of the system, excluding the possibility

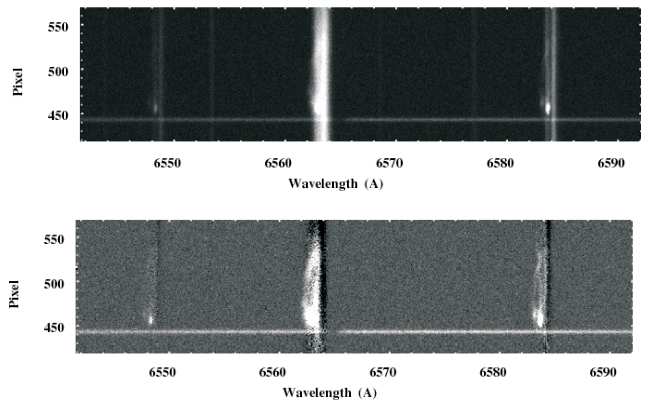

Fig. 2 Single-order echelle spectrograph of the jet system covering both Hα and [NII] emission lines. The slit is oriented along the jet direction with a position angle of 315°. Upper panel: Wavelength calibrated single-order echelle spectrograph of the jet. Note that the jet is clearly resolved into two distinct velocity components which are especially highlighted by the [NII] emission lines that have a smaller thermal dispersion than Hα. Line emission from both the receding and the approaching shells of the HII region are well resolved and presented. Lower panel: Net emission from the jet system after careful background subtraction.

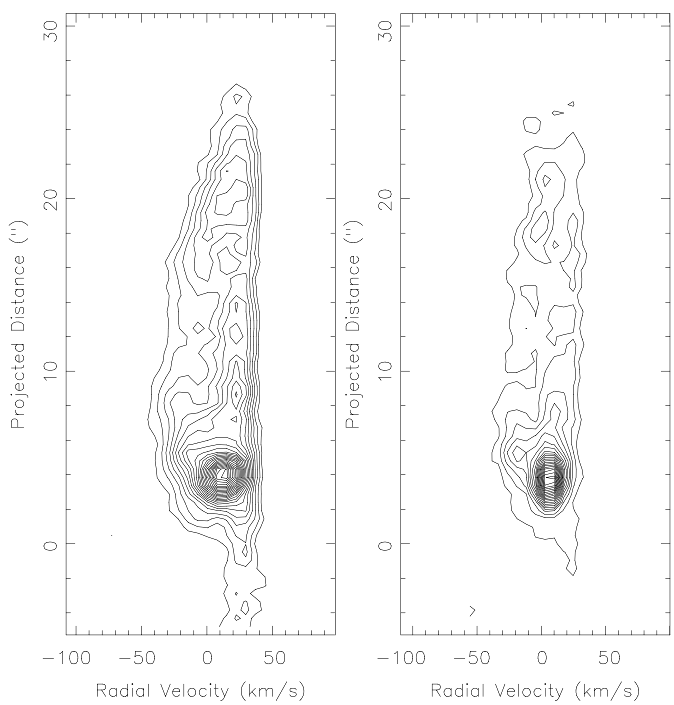

Fig. 3 Position-Velocity diagrams of the Hα (left panel) and [NII] λ6583 emission (right panel) from the jet. The radial velocity in the abscissa is calibrated to the heliocentric rest frame. The ordinate indicates the projected distance from the jet source, the position of which is marked as zero in the plot.

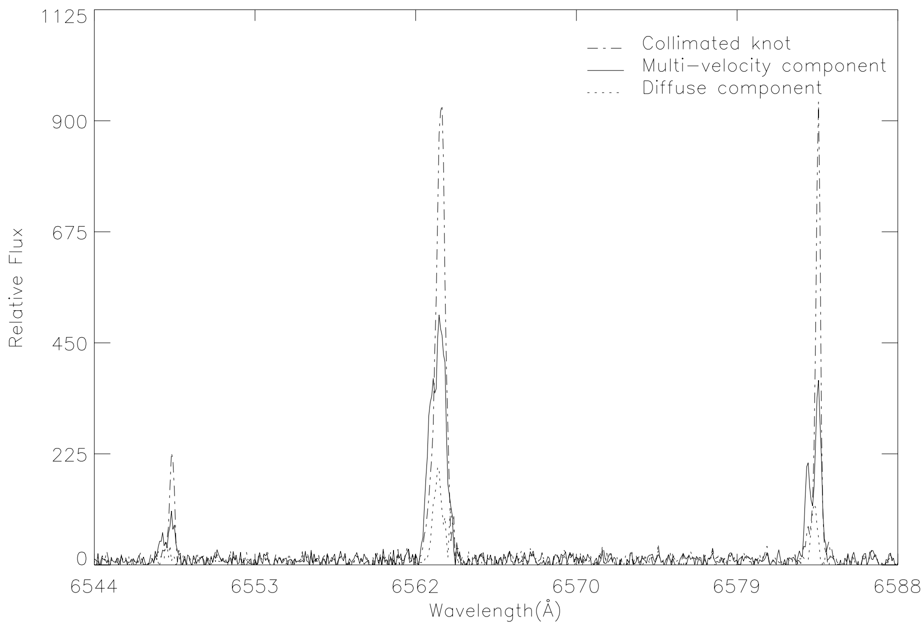

Fig. 4 Echelle spectra of the different jet components. Note the complex profiles associated with Hα and [NII] λ6548,λ6583 and their evolution along the jet direction.

that evaporated clumps of gas happen to be projected in the close vicinity of the energy source, which otherwise cannot be reconciled with the detection of the HVC or the two fold velocity structures.

Furthermore, the well-resolved data permit us to distinguish between the physically related jet components with distinct RV, which points to a clearer physical picture of the jet. It is composed of (1) a HVC attributed to a fast stream that appears at the position of the collimated part of the jet and remains propagating at roughly a constant speed until it meets the more extensive portion and slows down, and (2) a LVC associated with gas probably entrained by former mass ejecta from the source, but which keeps being photoevaporated by the strong UV field of Rosette as inferred from the kinematics of the LVC. It shows a RV in good agreement with a fast dissipating envelope or sheath of the jet moving at roughly the speed of sound of about 10 km s^{-1} (Johnstone et al. 1998). This argument will be further elaborated in the following sections.

4 SPECTRAL PROPERTIES OF THE JET SYSTEM

The single-order echelle spectrum of the energy source is presented as a solid line in Figure 4, in which Hα is broad in emission but shows a complex profile. It indicates signatures of absorption in both its blue and red wings, likely suggesting the coexistence of mass outflow and inflow. This agrees with the jet nature of the young stellar object. Note that the double peaked profile associated with the forbidden [NII] emission results from imperfect background subtraction. The red component is a residual of the strong but inhomogeneous background emission. This also affected the Hα emission, which is heavily blended with the nebular emission. Figure 4 also shows an evolution of the Hα profile along the jet direction, which reveals the change in the kinematics of the gas while it propagates away from the energy source. A third peak is clearly seen in the [NII] emission lines originating from the collimated part of the jet, in accordance with the presence of the HVC that keeps marching forward with a constant velocity until it merges into the diffuse knot and decelerates.

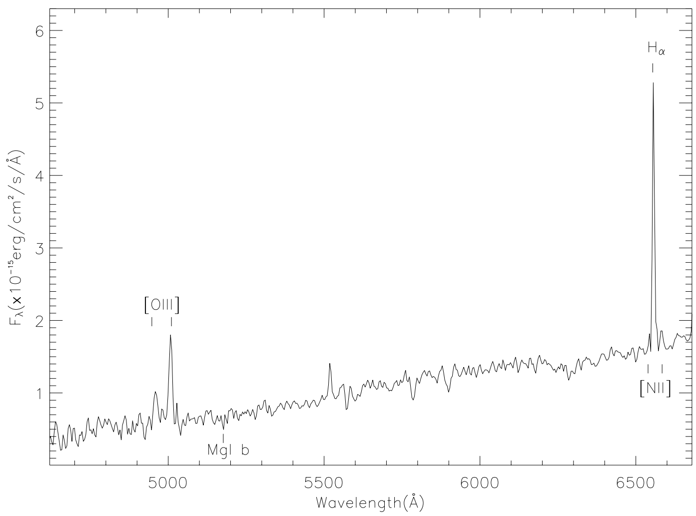

Fig. 5 Low-resolution spectrum of the jet source covering both Hα and the [OIII] emission lines. Note the red continuum of the energy source with a late spectral type.

The low-resolution spectrum of the jet source is presented in Figure 5, which primarily illustrates moderate Hα, prominent [OIII] emission and very likely shows a late spectral type with a red continuum in the optical. Low-resolution spectroscopy was employed due to the faintness of the energy source in the optical at the large distance of Rosette of 1.5 kpc (Dorland & Montmerle 1987). As a result, the Hα emission is hardly resolved from the nearby [NII] emission lines. However, its high state of excitation is revealed by the prominent [OIII] emission lines at $\lambda\lambda$4959 and 5007, which strongly suggests a fully ionized origin of at least the outer layers of the associated relic disk. This is corroborated by the detection of strong forbidden [OIII] emission lines in the jet by the multi-order echellograms and may lead to a rapid photodissipation of the system as stated below.

5 PHOTOIONIZATION AND PHYSICAL PARAMETERS OF THE JET

A close investigation of the dominant exciting sources of Rosette (please refer to fig. 7 of Li et al. 2007) at an adopted distance of 1.5 kpc (Dorland & Montmerle 1987) shows the combined impact of ionizing photons at a rate of $7.9 \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ on HH 890 and its energy source. The intensity of photoionization is about an order of magnitude higher than that encountered by similar jets in the vicinity of σ Orionis (Reipurth et al. 1998) and around the Trapezium stars (Bally et al. 2000). Electron density of the collimated part of the jet was derived from the line ratio of the [SII] doublet λ6717/λ6731 from our multi-order echelle spectroscopy along the jet direction. The standard method for an ionized nebula (Osterbrock 1989) was employed in the calculation. This yields an electron density of about $5 \times 10^3\,\mathrm{cm}^{-3}$.

Considering a jet lying in the plane of the sky of thickness t and uniform electron density n_e, its state of ionization can be maintained if

$$n_e^2 t\alpha \leq S(4\pi r^2)^{-1}, \qquad (1)$$

where α is the recombination factor ($2 \times 10^{-13}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$) for ionized hydrogen at 10^4 K in the ionization front. In the case of the HH 890 jet, a width of the collimated part of the jet of about $1.6''$ (3.6×10^{16} cm) was estimated. When inserted into Equation (1), a full ionization of the jet would require $n_e \leq 3.3 \times 10^3\,\mathrm{cm}^{-3}$, lower than the electron density of the HH 890 jet as presented above. A full ionization origin

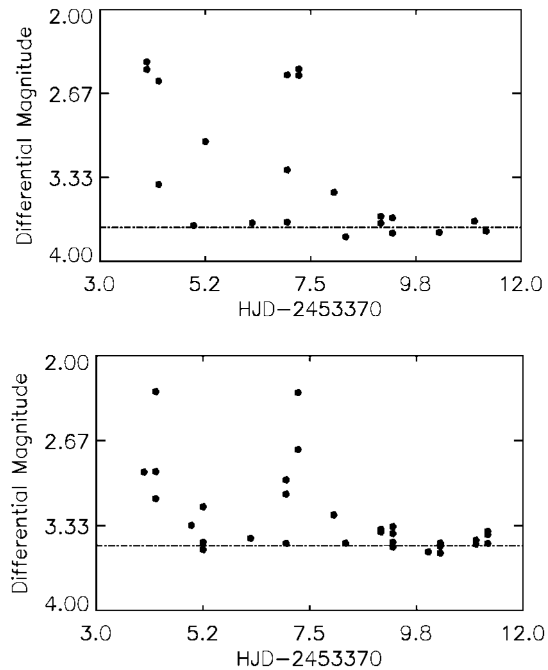

Fig. 6 Light variations of the jet source in both R (upper panel) and I (lower panel). Note the detection of the two flare-like events with similar amplitudes in both filters. The dot-dashed line in each panel indicates a fitted normal level of the brightness of the jet source with the large amplitude variations cancelled.

of the collimated part of the jet is thus not supported by this investigation. The strong UV radiation field, however, does lead to a continuous ionization of a large majority or at least the sheath of the jet as demonstrated by the detection of the prominent [OIII] emission lines.

Note that the jet system is located in close vicinity to a group of early B type stars (please refer to fig. 7 of Li et al. 2007), whose peak of emission is centered in the far-ultraviolet (FUV). According to the theoretical study of photoevaporation of gas clumps in HII regions by Johnstone et al. (1998), the intensive FUV radiation of Rosette will heat up the neutral core of the HH 890 jet, create a photodissociated region and generate subsonic neutral flows into the ionization front in the sheath, where extreme-ultraviolet (EUV) ionization from the OB stars plays a major role. Beyond the ionization front, the EUV ionization produces supersonic flows of outgoing gas into the ionized medium of the Rosette. This causes the dissipation of the jet material at a speed on the order of 1–2 times that of the local speed of sound, which is in good agreement with our measurement of a mean RV of 10 km s $^{-1}$ in the LVC. We thus conclude that it is the combined efforts of the FUV heating and the EUV ionization that resulted in the abnormally extensive appearance of the jet components with a high-state of excitation. Both the relic disk and the jet are engaged in this fast photodissipation by the OB stars, which may lead to a fate that dissolves the jet. This implies that we are likely spotting the last stages of jet evolution or dilution in the photoionzed medium of Rosette.

6 VARIABILITY OF THE JET SOURCE

Results from the photometric monitoring in R and I were presented by Figure 6a and 6b, respectively. It is clear that both lightcurves show anomalously strong photometric variations in a largely consistent way in both bands. This convinces us that the large amplitude variations are true in light of the small photometric uncertainty in each band (please refer to Sect. 2.2). Furthermore, possibly two consecutive eruptive events with similar amplitudes of $\sim$1.4 mag in R and 1.25 mag in I, respectively, were detected during the 13 day monitoring campaign. The large amplitude of variation is commensurate with the young evolutionary status of the energy source. The erratic light variations are most likely attributed to prominent chromospheric activity rather than possibly unsteady mass accretion associated with normal classical T Tauri stars.

7 SUMMARY

Based on high-quality echelle spectroscopy by the Blanco 4m telescope of CTIO, we present a kinematical study of the HH 890 jet for the first time, which is only the second jet candidate identified in the central cavity of the Rosette Nebula. This kinematical study clarifies the physical nature of the jet system. The collimated part of the jet clearly shows two distinct velocity components i.e. a HVC with a RV of -39 km s^{-1} and a LVC with a RV of -9 km s^{-1} with respect to the rest frame of Rosette. We infer that the collimated jet is composed of a fast moving stream that remains propagating at high speed into the photoionized medium, and a slow moving envelope or former mass ejecta dissolving at roughly the speed of sound. This jet system, along with the HH 889 jet (Li et al. 2007), is believed to be in the process of fast dissipation due to the harsh UV radiation field in which they reside. Our time-series photometric observations signify, on the other hand, a highly variable nature of the jet source, in agreement with its young stage of evolution and its possible association with a relic disk that engaged in photoerosion and dissipation.

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