Vampire Slaying in *Buffy the Vampire Slayer* May Result from Disrupted Ion Signaling

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Introduction

Buffy the Vampire Slayer ("*BtVS*") was an American television show featuring 144 episodes that premiered between 1997-2003. Early into its seven-season run, it gained a strong cult following and defined itself as an important part of American popular culture (Gross and Altman, 2017; Schwab). It continues to be critically analyzed by academics across a multitude of disciplines such as philosophy (South, 2003) and religion (Mills et al., 2013). Few studies have attempted to view the show from a quantitative perspective (see: ecological stability of vampires [Thomas, n.d.]; gendered biting patterns [Shapiro, 2008]). Here, we use a quantitative approach to connect observational measurements from *BtVS* to physiological studies. We then build a scientific model for vampire slaying, which we explore to make predictions about novel slayage techniques. This investigation aims to both deepen the lore of the Buffyverse and provide the basis for more robust analyses of *BtVS*.

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Analysis

Over the course of the series, we witness five ways to slay a vampire: staking ("The Harvest," 1.2), direct sunlight ("Who Are You," 4.16), fire ("Bargaining (Part 1)," 6.1), holy water ("Helpless," 3.12), and decapitation ("Who Are You," 4.16). If successfully implemented, a chain of events will proceed until a vampire is completely reduced to dust (Fig. 1A). Within the Buffyverse, this is rationalized as a mystical event, but it may be grounded in real, physiological phenomena. When analyzing vampire slaying frame-by-frame, for example, we observe two discrete, non-spontaneous events (Fig. 1B). Building on this observation, we will define *signaling* as the events that occur between staking and the moment that dust first begins to appear. Once completed, *dusting* will take place, in which dust spreads until the vampire is completely consumed.

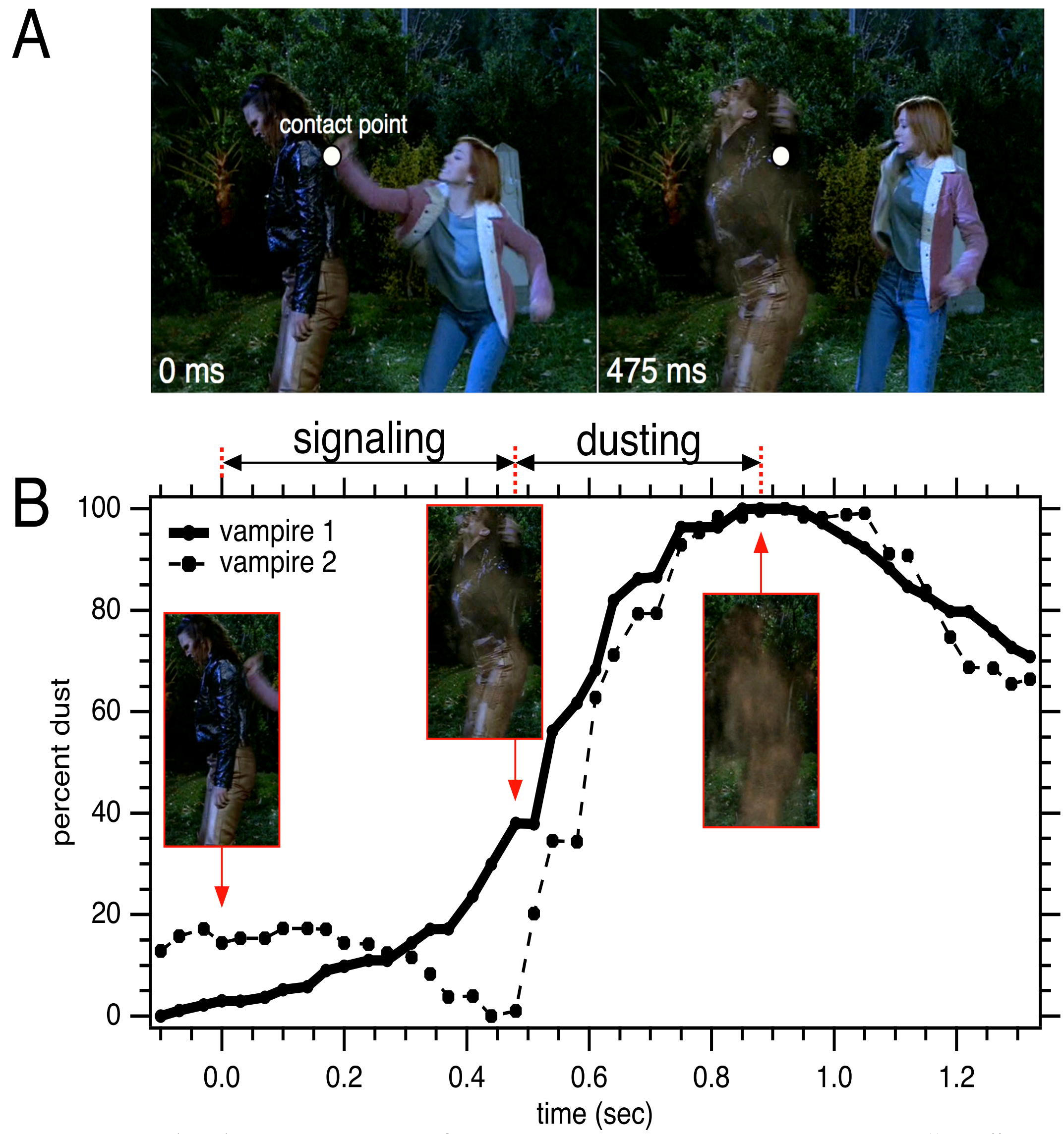

Figure 1: (A) An exemplar for staking at 0 milliseconds ("ms") and 475 milliseconds after contact ("Listening to Fear" 5.9). (B) We can quantify signaling and dusting times by measuring the average pixel intensity across each frame.

Signaling

Fig. 1A reveals that after signaling, every part of the body begins dusting simultaneously and at a similar rate. To quantify this observation, we can record vampire signaling times throughout the first five seasons of *BtVS* (Table 1). We observe that each slaying technique takes a different amount of time to proceed, implying different physiological mechanisms.

Slayage type	*Time - t* (seconds)	*Number of staking instances - N*
Staking	0.2 ± 0.8	62
Sunlight	1.9	1
Fire	5.9 ± 0.8	2
Consuming holy water	44.3	1
Decapitation	0.8 ± 0.4	3

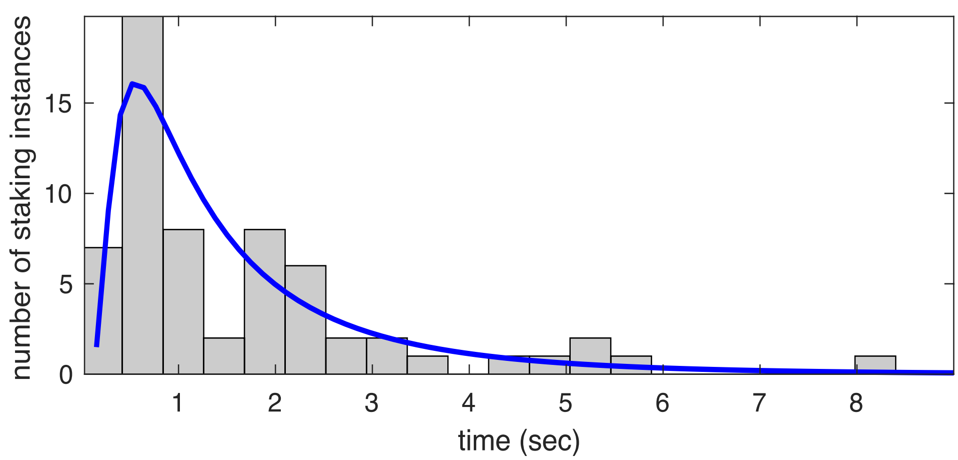

Table 1: (Top) Digitally recorded times for signaling over N occurrences, represented as mean ± standard deviation of t. (Bottom) Distribution of staking signaling times reveals a lognormal distribution. For this reason, we represent the set as mean ± standard deviation of ln (t).

Our recordings in Table 1 reveal an impressive biological feat. In 800 milliseconds, blood in the artery can only travel 40 centimeters, yet within the same period of time, a vampire's entire body can respond to the effect of a staked heart (Fig 1A, Jorgensen et al., 1992). Physiologically, electrical impulses are an excellent candidate for achieving this type of speed (traveling 80 meters in 800 milliseconds) (Kraus, 1969). To better understand how electrical impulses connect to vampire slayage, we can carefully analyze the staking process.

Staking

To properly stake a vampire, a wooden object must come into contact with a vampire heart. This is extremely specific: if a vampire is stabbed through the heart with a non-wooden object ("Into the Woods," 5.10) or is stabbed with a wooden object elsewhere ("Graduation Day (Part 1)," 3.21), dusting will not occur.

After staking, wood is not turned to dust as long as it is removed completely after contact ("Listening to Fear," 5.9). This allows it to be reused. It also does not lose its ability to slay a vampire over time (see "Mr. Pointy," "Becoming (Part 2)," 2.21). This suggests that wood is a catalyst for which only the outermost surface of the wood is relevant. Our wood stake consists of two main components: lignin and carbohydrates (Pettersen, 1984). We are primarily interested in lignin: while carbohydrates are common across organisms, lignin is only present in plants, introducing a unique candidate for staking (Sakagami et al., 2005).

Human hearts, at the cellular level, create a vast majority of electrical impulses by moving three ions—calcium (Ca^{2+}), sodium (Na^{+}), and potassium (K^{+}) (Priest and McDermott, 2015). This phenomenon is termed "ion signaling." If we assume that vampire hearts are analogous to human hearts, we can reframe the staking process as a chemical interaction between lignin (at the surface of wood) and positively charged ions. Ca^{2+} has been observed to bind to lignin via chemical groups that form naturally on the surface of wood (Wang and Piao, 2011; Pandey, 2005; Torre et al., 1992). Studies on Na^{+} and K^{+} are less robust, but also appear to bind to wood (Karagöz et al., 2005; Garcia-Valls and Hatton, 2003).

This allows us to define a working model: as a stake is inserted into a vampire's heart, cations, or positively charged ions, cling to the surface of the stake. These ions, now attached to wood, cannot be moved, hindering the heart's ability to create electrical impulses. As expected, this has serious consequences: a lack of calcium ions in the heart, for instance, can induce cardiac arrest in humans (Soar et al., 2010). We propose that a similar mechanism is involved in vampire dusting, which we can frame using observations from other slaying techniques.

Sunlight

Vampires are extremely sensitive to sunlight and can be completely dusted by excessive exposure. This presents a dose-dependent form of slaying, since vampires have interacted with small amounts of sunlight and survived ("Spiral," 5.20). To investigate this phenomenon, we consider that vampires are night-dwelling creatures and are unaffected by moonlight. This allows us to compare the types of light reaching Earth's surface from both sources (Mecherikunnel, 1980; Cramer et al., 2013; van der Steen, 2015).

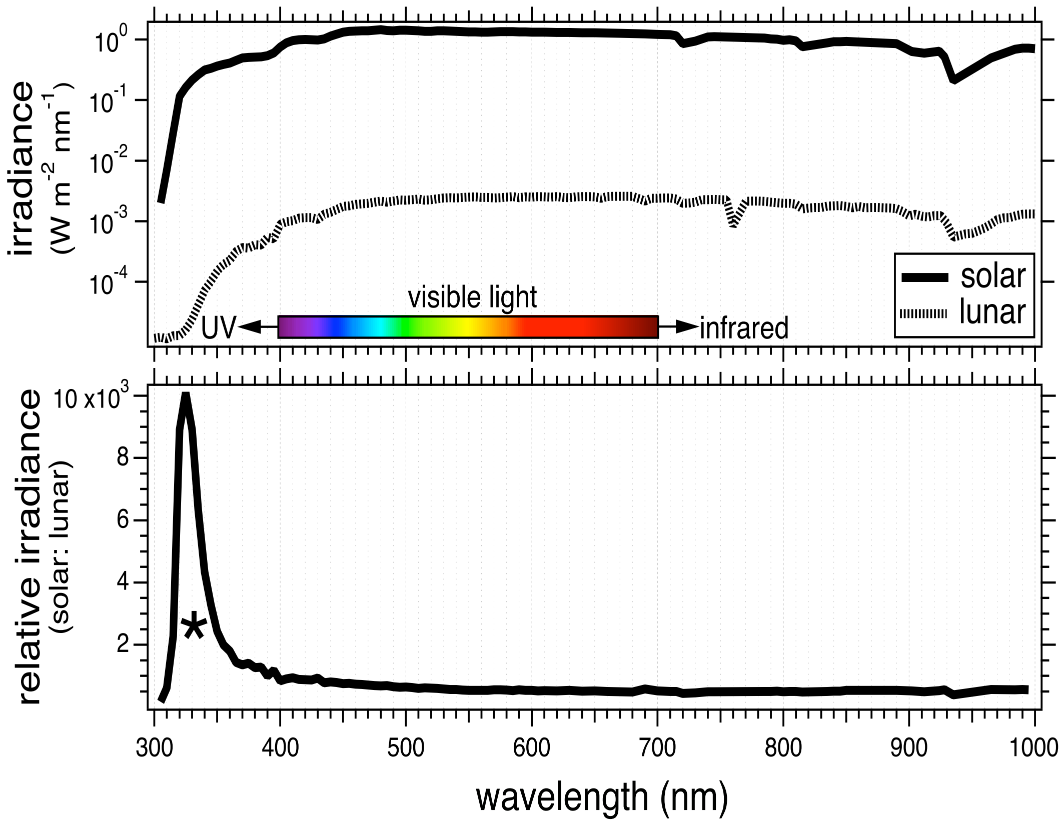

Figure 2: (Top) Solar and lunar intensities of different types of light (in nanometers, "nm") as measured on Earth's surface. (Below) Comparing the two values reveal wavelengths of light that are relatively prominent (* during the day but not at night.

Fig. 2 reveals a peak at 325 nanometers (ultraviolet light, "UV"), where sunlight is 10,000 times more intense than moonlight. This is nearly ten times as intense as our visible and infrared ("IR") regions. In addition, the surfaces of common features in Sunnydale (such as grass and concrete) reflect less than 10% of UV light that hits them (Diffey et al., 1995). This predicts that vampires should be largely unaffected by areas with indirect light such as daytime shade ("After Life," 6.3).

Ultraviolet rays have been observed to produce reactive oxygen species ("ROS") in the mitochondria of skin cells, which is a catch-all term for chemistries that (1) contain an oxygen atom and (2) are highly reactive (Ghanizadeh Kazerouni and Seebacher, 2016). This class of chemicals is regularly produced in humans and can damage muscle by blocking ion channels, similar to our proposed staking mechanism (Ghanizadeh Kazerouni and Seebacher, 2016). Humans typically have natural defenses in the form of antioxidants, which come from vitamins gained in food (Ghanizadeh Kazerouni et al., 2015). However, vampires have significant dietary restrictions, relying only on the antioxidants gained from human blood.

We can attempt to justify this phenomenon further. Using an instance of sunlight slayage from "Who Are You," we estimate that for every 9 photons of ultraviolet light that touch skin cells, one ROS molecule is created (Calculation A). Over a full 1.9 second exposure (Table 1), the total amount of ROS produced from one exposed skin cell can silence all ion signaling in an entire neuron (Buchholtz et al., 2002). The assessment that sun exposure in "Who Are You" affects 10^{11} skin cells gives credibility to the idea that a meaningful amount of electrical impulses can be blocked by ROS alone.

Fire

Vampires that are ignited have a 5.9 second signaling time (Table 1). We can approach this observation from two perspectives: how fire affects ion signaling and the apparent flammability of vampires ("Bargaining (Part 1)").

There are several possibilities for how fire can affect ion signaling. Subjecting smooth muscle to extremely high temperatures for only a few seconds can irreversibly inhibit muscle signaling (Dyrda et al., 2011), suggesting that a 5.9 second signaling time is feasible. Burn patients have also been observed to have impaired calcium channels in the heart (Murphy et al., 1999) and exhibit low calcium concentrations in general (Klein, 2011), suggesting a complementary but alternative pathway to our ion signaling model.

The quick spread of fire may be attributable to a form of spontaneous human combustion by which fire on humans spreads quickly due the burning of fat (Gromb et al., 2000). One hypothesis for this mechanism is that built-up acetone may be the cause, which is naturally produced if liver cells are starved or are subjected to low-carb diets (Ford, 2012; Likhodii et al., 2002). This hypothesis suggests that vampire flammability could be result of a lack of carbohydrates, since vampires do not receive enough from a whole-blood diet.

Holy water

Within *BtVS*, holy water burns vampire skin, though no vampire has been slain by excessive skin contact to holy water. Only one fatal act of mistakenly drinking holy water has been depicted ("Helpless"). For a typical human, swallowed liquid takes 8.5 seconds to reach the stomach and minutes to hours for liquid to leave the stomach (Mashimo and Goyal, 2006; Marcus and Lengemann, 1962). Our measured 44-second dusting ("Helpless") allows us to pinpoint the reaction within the main stomach.

Within "Helpless," the vampire undergoes three substages of signaling: normal behavior (18 seconds), discomfort (13 seconds), and visible burning (14 seconds). (We assume that the "visible burning" substage is unrelated to fire since it takes considerably longer than fire slayage). The likely culprit for burning is gastric acid within the stomach, which is normally contained by a mucosal layer that protects nearby smooth muscle (Phillipson, 2004). Reactive oxygen species (or ROS, implicated in sunlight slayage) can readily dissolve this mucosal layer, as can certain strains of bacteria (Suzuki et al., 2012; Hoskins and Boulding, 1981). However, a lack of understanding about the properties of holy water limit our ability to narrow possible mucus-degrading byproducts in gastric acid. Holy water is also a likely indicator for the mystical part of vampires that a physiological model cannot reach.

Decapitation

Decapitation has an average signaling time of 800 milliseconds and is the second-most frequent slayage type in *BtVS*. In a study aimed at understanding laboratory rat euthanasia, it was observed that post-decapitation, both sections of a rat exhibited spastic movements for several seconds (van Rijn et al., 2011). This lengthy period of time suggests we cannot explain the speed of signaling in vampires by a complete silencing of ionic activity. However, a lack of published research on decapitation at millisecond resolution limits our ability to build associations between decapitation and ion signaling. We leave this as an open question in our model.

Dusting

Having completed signaling, a vampire must completely turn to dust in 500 milliseconds. This is not trivial, since skin, muscle, and bone must entirely disintegrate. A prevailing thought might be that vampires are similar to the dead and are thus reverted back to their native form: dust. However, anything attached to the vampire, including clothing, reduces to dust as well ("Anne," 3.1). Since dusting is invariant of the material, we can only consider a strong heat source, which cremates the vampire. But searing a vampire in only 500 milliseconds is a tall order, and since vampire dust does not visibly burn humans immediately after dusting ("Anne"), it does not appear to be physiologically explainable. For this reason, we consider dusting to be a mystical product of vampirism.

Discussion

Here, we have built a framework that suggests ion signaling plays an important role in vampire slayage throughout the Buffyverse. There are many useful observational byproducts of this model, one of which is the ability for Sunnydale residents to protect themselves against vampire attacks. For instance, an engineer could design a UV laser pointer (< 320 nanometers) that mimics ROS production for dusting vampires from afar (see Calculation A for estimated laser intensities). There are also plenty of ion channel agonists, such as prescription calcium channel blockers, that may allow for indirect dusting (Elliott and Venkata, 2011). We propose another, more novel solution that simultaneously tests the validity of our model.

It has been shown that organic chemistries can be irradiated in a laboratory and compressed into an aerosol to create a ROS spray (Manfrin et al., 2019). Depending on the chemical stability of reactive oxygen species in aerosol form, we imagine an industrially-produced consumer product that can be used as a vampire repellant, similar to pepper spray. This product would be particularly useful for Sunnydale residents: firstly, this aerosol mimics the effect of UV light without needing to lure vampires into sunlight or arm residents with high-intensity UV lasers. Secondly, aerosols can be deployed from afar without requiring much accuracy, negating the need for extensive training. Thirdly, it is portable and reusable, allowing residents that carry it on-the-go in preparation for unexpected vampire appearances. Since our model predicts that such a robust application of this spray would block ion channels in vampires and lead to dusting, testing this product also gauges the legitimacy of our model.

Complementarily, vampires can attempt to counteract the effects of our ROS spray by increasing their antioxidant intake. According to our model, antioxidants can lessen the damage of reactive oxygen species, requiring a larger exposure to induce dusting. Vampires have been observed to eat normal foods ("Hush," 4.10), suggesting that additions to their diet is possible.

Conclusion: A Modest Proposal

By quantifying seven seasons of vampire slayage throughout *Buffy the Vampire Slayer*, we have built an observational model that suggests that ion channels may play a role in vampire vulnerability. Through this model, we attempt explain how ion channels can be associated with various forms of slayage, and suggest a new defense mechanism against vampires by aerosolizing photoproducts of organic compounds. We hope this investigation serves the Buffy community by influencing future works and encouraging deeper investigations into vampire physiology.

Methods

Fig. 1. Digital recordings were performed using VLC media player. Frame-by-frame analysis was performed using VLC and MATLAB. In brief, a series of images were exported from VLC. Each image was imported, cropped, and separated into red, green, and blue pixel values (RGB) in MATLAB. For each pixel, p, we isolated noise via the equation p_{red} - p_{blue}. All resulting pixel values were averaged and normalized to quantify our "percent dust" metric. All code and analysis materials are available upon request.

Fig. 2. Solar intensities (Mecherikunnel, 1980) were exported from PDF format to CSV manually. Lunar intensities from Cramer et al. (2013) did not sufficiently reach into UV. For this reason, an independent dataset from van der Steen (2015) was compared to Cramer et al. (2013), observed to be similar in visible and infrared regions, and used for the bulk of the analysis. All calculations were performed in MATLAB and plotted in IgorPro.

Calculation A

We numerically integrate Figure 2 between 320 and 330 nanometers (in which sunlight is >8900 times more prominent than moonlight) which yields 1.635 W m^{-2}. In "Who Are You" (4.16), we observe that the vampire's full face and palms are exposed. The average surface area of a face is 0.0375 m^2 (Gross and Roppel, 2017) and two palms are 0.054 m^2 (Kaye and Konz, 1986), yielding a total exposed skin surface area of 0.092 m^2. Since our vampire begins turning to dust in 1.9 seconds, the total amount of energy absorbed is,

$$(1.635 \text{ W m}^{-2} \times 0.092 \text{ m}^2) \times 1.9 \text{ s} = 0.28 \text{ J}$$

A study by Hanson and Clegg exposed sections of isolated skin to UV light and measured ROS production in the outermost layer of the skin (Hanson and Clegg, 2002). We linearly interpolate their result to reveal that 10×10^{-6} M ROS are produced by UV-irradiated skin over 1.9 seconds.

The outermost region of skin has 5×10^{10} skin cells m^{-2} (Bergstresser et al., 1978) and is 15 layers thick, spanning 10 µm, such that there are 7.5×10^{15} skin cells m^{-3} (Holbrook and Odland, 1974). We convert our estimate of 10×10^{-6}M ROS to 6×10^{21} molecules of ROS m^{-3} and observe that each skin cell produces,

6×10^{21} molecules m^{-3} / 7.5×10^{15} cells m^{-3} = 8×10^{5} molecules ROS / cell.

The sun delivers 5×10^{18} photons of UV light to every square meter of vampire skin. This is distributed across all 15 layers of skin cells, allowing us to state that each cell interacts with 7×10^{6} photons. This allows us to conclude that one ROS molecule is generated for every 9 photons of ultraviolet light that touches it.

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