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Antarctica's Kiss-Shot

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Abstract
In the light novel series *Monogatari*, the legendary vampire Kiss-Shot Acerola-Orion Heart-Under-Blade once travelled to Antarctica, wishing to see the aurora australis. However, her method of leaving the continent was to jump from the South Pole to her next destination. The recoil from this jump 'threatened to destroy' the Antarctic landmass. This paper will discuss the implications of this jump using comparisons to crater forming impact events. After considering the composition of Antarctica, the energy generated by said jump would have been greater than the explosive yield of the global nuclear arsenal.

Keywords: *Light Novel; Anime; Physics; Impact Event; Monogatari; Kiss-Shot Acerola-Orion Heart-Under-Blade*

Background
Nisio Isin's *Monogatari* light novel series and the subsequent creative Studio Shaft anime adaptation follows Koyomi Araragi, a third year high school student. After becoming a vampire prior to the academic year, he finds himself meeting others afflicted by 怪異 (pronounced kai-i). Translated from Japanese to 'strangeness' or 'aberrations', these supernatural phenomena are based on myths or legends. Never far from our protagonist, often hiding in the shadows, is the mysterious blonde-haired small child Shinobu Oshino. However, before taking this form as a Mister Donut loving young girl, she was the powerful 598 year old vampire, Kiss-Shot Acerola-Orion Heart-Under-Blade, that previously attacked Araragi [1]. Throughout the series, Shinobu boasts of some of the phenomenal feats she was capable of in her prime – befitting one that could easily 'make the Earth disappear' [2].

During her travels to the South Pole to enjoy the aurora, she wanted her next destination to be somewhere around the Pacific. Planning to first land in the ocean for a refreshing swim, she jumped from Antarctica, and coincidentally landed in Japan. However, 'the recoil of the jump threatened to destroy the Antarctic landmass' [2]. Shinobu states she 'took care not to do so completely' [2], but the impact would still have been considerable. A common anime trope is the creation of a crater during moments when a powerful character displays their immense strength [3], as shown in Figure 1. Assuming Kiss-shot's jump would have followed this theme, this paper will make an estimate of the energy required to create such a crater in Antarctica.


Figure 1 – Depiction of Kiss-shot's jump from Antarctica, including an example of the 'crater trope'. (Photo credit: Atlastrix).

Antarctica
Antarctica is the southernmost continent, but also the coldest, with 98% of the land covered by thick ice [4]. The ice sheet contains 80% of the world's fresh water, reaching a maximum thickness of 4776m, with a mean thickness of 2160m [5]. As described in Table 1, the physical properties of ice are dependent on depth within the ice sheet. The topmost layer of ice, firn, is due to the densification of surface snow [6]. This is followed by further sintered firn, which

possesses an increased density, and porous glacial ice. The final, most compact layer of the Antarctic ice sheet is made up of the densest type of ice, glacial ice, which extends down to the main continental shield [7]. The main continent was not always barren and icy, with volcanic activity common in the past. This has led to the composition of the continental layer becoming a mixture of igneous and metamorphic rocks [8]. The physical properties of this layer are also described in Table 1.

Material	Density	Compressive Strength	Depth Limit
Firn	550 kgm^{-3}	20.4 MPa	65m
Sintered	720 kgm^{-3}	27.1 MPa	80m
Porous	745 kgm^{-3}	36.5 MPa	120m
Dense	897 kgm^{-3}	49.5 MPa	2160m
Rock	2978 kgm^{-3}	151.4 MPa	>2160m

Table 1 – Breakdown of the average composition of Antarctica by layer. Firn, Sintered, Porous and Dense refer to the ice layer, and Rock assumes a mix of igneous and metamorphic rock. Average values are taken from [6, 7, 9, 10 & 11].

Here, the maximum depth of each layer of the ice sheet has been taken as the mean depth, 2160m. Compressive strength is a measure of stress, defined by the force per unit area. This limit describes the pressure required to permanently affect the long range order of a material [12], in this case the crystalline structure of ice or the minerals contained within the Antarctic continental shelf.

Impact Energy

The Charters model [13] relates the energy of formation of a crater due to an impact event to the deformation stress in the target material. In this case, the 'impact event' is the recoil of Kiss Shot's jump, and is described in Equation 1 as

$$E = 2\pi \int Sr^2 dr = \frac{2\pi}{3} \sum S_i (\Delta r_i)^3 \qquad (1)$$

where r is the radial depth of the hemispherical crater, and S the deformation stress. Simplifying the continent of Antarctica into discrete layers of material, as described in Table 1, turns the integral into the sum of energies of each respective layer. Charters does not explicitly define the appropriate stress to use as deformation stress within the model, therefore in this calculation compressive strength will be used. Here, a crater depth of 12km has been assumed. In accordance with Charters model, this leads to a crater diameter of 24km. This is far less than the 150km Chicxulub crater, the crater that caused the Cretaceous-Paleogene extinction event [14]. Since the Chicxulub impact caused a global tsunami [15], and the rest of the world was largely unaffected by Kiss-shot's jump, this is a reasonable estimate of the crater size. Substituting the values of compressive strength and depth intervals for each layer from Table 1 into Equation 1 gives:

$$E = 10^6 \frac{2\pi}{3} [(20.4\ Pa)(65\ m)^3 + (27.1\ Pa)(15\ m)^3 + (36.5\ Pa)(40\ m)^3 + (49.5\ Pa)(2040\ m)^3 + (151.4\ Pa)(9840\ m)^3] = 3.03 \times 10^{20}\ J$$

The total energy to cause the 12km wide crater is 303 EJ, and is of a similar order of magnitude to the global energy consumption, 500 EJ [16], and greater than the explosive yield of the global nuclear arsenal [17].

Discussion

Ice is found in many forms throughout the universe, however, the most abundant form on Earth are hexagonal crystals, also known as ice Ih [6]. This simple calculation assumes that the layers of ice distributed throughout the sheet are isotropic, and ice crystals are compressed uniaxially through the c-axis of the crystal. Any dislocation of ice along the basal planes of the crystal – known as basal glide – due to shear stress would require much less energy [18][19]. However, this would only affect surface ice distributed radially around the jump as the shockwave propagates away from Kiss-Shot. There is also a seasonal dependence of ice density with temperature; Antarctica's climate varies from -20°C to -60°C from summer to winter within the interior plateau [20], and this would affect the compaction of snow accordingly. However, since the majority of the energy required for this crater is due to the compression of Antarctica's rock layer, the difference in energy is likely to be negligible.

The 303 exajoules transmitted into Antarctica would only represent part of the energy generated by Kiss-shot's inhuman muscles, with fractions also being converted into other forms of energy. In particular, the heat generated from this jump will be explored in future work.

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