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The 22 September 1979 Vela Incident: The Detected Double-Flash

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ABSTRACT

On 22 September 1979 two optical sensors on U.S. satellite Vela 6911 detected a double-flash of light that appeared characteristic of an atmospheric nuclear explosion conducted over the southern Atlantic or Indian Ocean. It became known as the Vela Incident, Event 747, or Alert 747. An anomaly between the amplitude of the two signals during the second pulse led a U.S. government expert panel established to assess the event to conclude in mid-1980 that a more likely explanation was the impact of a small meteoroid on the satellite, the debris from which reflected sunlight into the sensors' field of view. No model was presented to support the contention, and a similar anomaly—known as background modulation—was a given for the second pulse of all confirmed explosions detected by Vela, though beginning later. Nonetheless, this event has remained the subject of intense debate. This article reviews the evidence and presents an updated analysis of the original Vela signal based on recently declassified literature and on modern knowledge of interplanetary dust and hyper velocity impact. Given the geometry of the satellite, and that the bulk of the surface comprised solar panels, much of the debris from any collision would be carried away from the sensors' field of view. Thus, a meteoroid collision appears much less likely than previously assumed. The double flash is instead consistent with a nuclear explosion, albeit detected by an aged satellite for which background modulation was abnormal and/or commenced earlier, also seen in post-event SYSTEM tests. A companion paper to be published in 2018 presents radionuclide and hydroacoustic evidence supporting the conclusion that the Vela Incident was a nuclear weapon test explosion.

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Introduction

On 22 September 1979, at 00:53 UTC, U.S. satellite Vela 6911 detected a double-flash of light that appeared characteristic of an atmospheric nuclear explosion. The two

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sensors on-board 6911, designated YCA and YVA, also known as bhangmeters, were specifically designed to detect just this sort of optical signal.[1] Vela 6911 was one of a fleet of satellites put into orbit between 1963 and 1970 to detect nuclear explosions above the surface of the Earth. Such tests had been prohibited by the 1963 Partial Test Ban Treaty (PTBT). At the time of the event, PTBT member states included, among many others, the United States, the Soviet Union, the United Kingdom, Israel, India, and South Africa.[2]

Known as the Vela Incident, Event 747, or Alert 747, it is believed to have occurred somewhere over the southern Atlantic or Indian Ocean, possibly near Prince Edward and Marion Islands at 46.7 S and 37.9 E, while the satellite looked from a position more over the South Atlantic approximately 110,000 km above the ocean (Figure 1). The precise nature of the event, and the responsible party if it was a nuclear explosion, remains the subject of debate. Several histories of the event and the discussion that followed have been published over the years, with Israel—possibly in collaboration with South Africa—often mentioned as being responsible for a nuclear weapon test conducted clandestinely in this region at the time.[3]

Following the detection, an enormous effort was put into analyzing the source of the signal, specifically its possible nuclear explosive character, via a wide-ranging search for corroborative evidence. We refer to the aforementioned reviews for details of most of these efforts, but note here that two other operational Vela satellites then

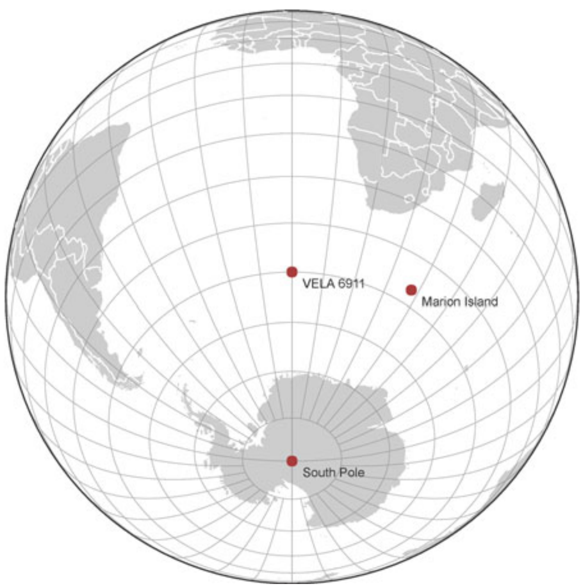

Figure 1. The surface position of Vela 6911 at the time of the Alert 747 flash, along with Marion Island close to the suspected site of the explosion about 2600 km to the east. The co-ordinate grid shows intervals of 10 degrees in both latitude and longitude. The full Earth disk was visible from the satellite's position. But the actual circular field of view considered by US government agencies for the putative nuclear event encompassed all of South Africa (including present-day Namibia), Botswana and a portion of Angola to the north, extended south to approximately the South Pole, west to skirt a few hundred kilometers off the east coast of South America and east to near the Crozet Island group (not shown here). All were in darkness, except for a small part of Antarctica.

in orbit did not detect the signal. In December 1977, Vela 6909, twin to 6911, had lost its atmospheric detection capability when its attitude control propellant was depleted and Earth orientation could no longer be maintained.[4] Thereafter, in the interest of maintaining a limited capability, the phasing maneuvers for the three remaining satellites (6911, 7033, and 7044) were suspended, leading to some loss in global coverage. Further, two Defense Support Program (DSP) satellites equipped with bhangmeters had coverage partially overlapping with 6911 but did not detect a signal; if Alert 747 was indeed due to an atmospheric nuclear test it was not detected by the other satellites, either because the event occurred in an area outside their view or the signal was attenuated by cloud covering much of the region.[5] A search for an infrared signature using the same two DSP satellites also proved negative.[6] This would not be surprising if thick cloud was in the area. Overall, this lack of independent confirmation by other monitoring satellites has never been considered to be a problem for the nuclear airburst interpretation of Alert 747.

Given Alert 747's potentially serious implications for nonproliferation efforts at the time, and its broad public interest, a panel of eight highly respected and expert scientists, headed by Massachusetts Institute of Technology professor Jack Ruina, was appointed by the Office of Science and Technology Policy (OSTP), part of the Executive Office of the President, to assess all the information. They received briefings by the various bodies that studied the original signal and searched for supporting data, and subsequently produced an unclassified summary of some of that work as well as their own conclusions.[7]

The report concluded that Alert 747 was unlikely to have originated from a nuclear explosion. This was primarily based on a larger-than-expected difference (compared to previously detected nuclear explosions) between the signal amplitudes for the two bhangmeters during the second pulse portion of the double light flash. The panel was also unconvinced by the evidence put forward to corroborate a nuclear explosion. The panel instead surmised that Alert 747 was one of a population of a hundred or so unexplained signals which the Vela satellites had detected over the years. These became known as the Vela zoo (members of which will be referred to here as zoo-ons). As a possible explanation, the panel proposed a meteoroid impact with the satellite, the debris from which scattered solar radiation into the view of the optical sensors. They used data from the Pioneer 10 interplanetary space probe as precedent for this scenario.

Some of the actual reports that the panel may have considered remained classified until about 2006, when several crucial reports were released, though not all of them in their entirety. Four of the most detailed and important are: Oetzel and Johnson, "Vela Meteoroid Evaluation, 1980"; Mauth, "Alert 747, 1980"; Horak, "Vela Event Alert 747", 1980; Sappenfield, Sowle, and McCartor, "Possible origins of Event 747 optical data, 1980." As they will be cited many times throughout this paper they will be hereafter referred to as OJ80, Ma80, Ho80, and SSM80.[8]

Information on nuclear weapon-design issues and/or technical capabilities of the Vela satellite systems had been redacted from these reports. Even so, much of the analysis, reasoning, and conclusions of their authors was retained, from which it is possible to make an independent assessment of the reports themselves as well as the Ruina panel's interpretation of them summarized in the panel's report, hereafter referred to as Ru80. Another major report was compiled by the Naval Research Laboratory (NRL). The report focused on possible hydroacoustic signatures but was never made publicly available. Some details from this report are available in other documents quoting the NRL Director of Research, which allows a reasonable reconstruction of the report's content and especially its conclusions. This is considered in an accompanying paper "The 22 September 1979 Vela incident—Part II: Radionuclide and hydroacoustic evidence for a nuclear explosion".

Presented here is a new and forensic analysis of technical aspects of both the Vela incident itself, as well as possible scenarios for its origin, which are contained in the aforementioned and several other reports. Brought to this new analysis is up-to-date information on the micrometeoroid environment and hypervelocity impacts. The plan of the paper is as follows. First, the physics of the double flash and the content of the Ruina panel's report are briefly reviewed. Following that, a closer look is taken at the two bhangmeter traces of Alert 747, members of the Vela zoo, and the possibility that Alert 747 was a zoo-on, including whether it could be explained by debris from a meteoroid collision. The next section examines work that has been performed since the Vela incident on possible explanations for the zoo, while nuclear explosion models constructed for the event are reviewed in the final section. A companion article analyzing possible radionuclide detections and hydroacoustic signal associated with the Vela incident is forthcoming in this journal (De Geer & Wright, 2018).

The double flash

Within a microsecond of detonation, the energy of a nuclear explosion is deposited in the device materials, forming a plasma with a temperature of some 10^7 Kelvin, comparable to that of the Sun's core. Prompt x-rays heat the immediately surrounding air to 10^6 K, which, along with the device debris, forms the initial fireball. The double-peak light flash of a nuclear airburst is a product of this hot fireball being first transparent, then opaque, and then transparent again as it expands into the cooler air.[9] Specifically, it is the shock front of the explosion - produced by the radiative and hydrodynamic expansion - and its energy budget via heating and cooling processes, that ultimately gives the unique flash signature.

The first pulse is a competition between the luminosity being an increasing function of the total emitting surface area and a decreasing function of a cooling temperature. Up to the first maximum, the former wins and then the latter takes over until the time of minimum. Subsequently, as expansion and cooling continue the shock becomes increasingly transparent, allowing more and more visible light to escape from the hotter interior and providing the second maximum, at which point the typical temperature is about 6000 K (Ma80). Further cooling due to the hydrodynamic expansion and radiative losses results in the luminosity decreasing again.

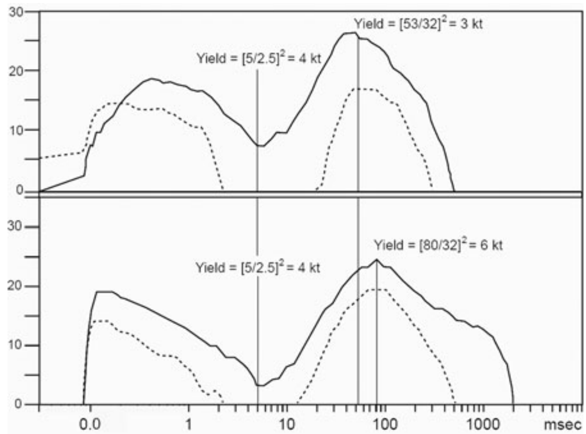

Figure 2. The signals recorded by the two Vela 6911 bhangmeters on 22 September 1979 (upper panel) and the signals recorded by the two Vela 6909 bhangmeters on 17 July 1974 of a French atmospheric test over Mururoa atoll (lower panel). The X-axis is time in milliseconds and, in common with the originals, semi-logarithmic with the portion up to 1.0 ms being linear. The Y-axis is signal amplitude, expressed as Level Discriminator (LD), and explained in OJ80, Ma80, and SSM80. In both panels, the solid line is from the most sensitive detector (YCA) and the dotted one from the less sensitive one (YVA). For much of the French time history, the difference is 5 LD units, as expected (OJ80), until they begin to diverge after 100 ms, whereas this is only the case for a portion of the Alert 747 trace. The approximate yields are estimated from the times of the minimum and the second maximum according to empirical formulae.

The physics of these processes depends only on the total input energy and not on how it is produced. In particular, the maximum and minimum of the double-peak flash do not depend on whether the input energy came from fission (e.g., a Trinity-type device) or fusion (e.g., a modern thermonuclear device), and thus is independent of design features. It is both the light intensity and its temporal variation that are unique to an atmospheric nuclear explosion, with the second peak lasting 100 times longer than the first and containing 99% of the energy. Other natural processes might be able to produce one or the other signature, but not both.[10]

Alert 747 signal—comparison to other nuclear explosions and derived yield

The 1979 double flash intensity-time plots are available in several reports, and are reproduced here in Figure 2.[11] The physical units of the Y-axis scale (signal amplitude) is not provided, but instead expressed in “level discriminator” (LD) units, for which a conversion factor to W/cm^2 is provided by Figure 11 in OJ80 for the most sensitive bhangmeter. Thus, the Alert 747 second pulse peak amplitude is approximately 10^{-8} W/cm^2. There are very little data available on other atmospheric nuclear tests for an unambiguous quantitative comparison of their time histories. Important exceptions are a double flash time history for the 4 kt Centaure explosion 270 m above Mururoa atoll on 17 July 1974, and a single detector flash plot for the 19 kt Dog test 317 m above the Nevada Test Site on 1 May 1952, which is expressed in watts of total thermal power.[12]

The optical flashes for Alert 747 and the Centaure events are shown in Figure 2. The apparent difference in shape between YCA and YVA for the first pulse of Alert 747 is likely due to the declassified data not being corrected for various instrumental artefacts. These include the trigger time disparity due to non-identical sensitivities, as well as a non-linearity distortion for YVA for low yield events.[13] Once these corrections are made, according to Ma80, there is "excellent YCA/YVA signature consistency through the first maximum pulse portion of the Alert 747 data." This sentiment is also expressed in SSM80, which states that "the apparent difference between the YC and YV data during the first pulse is largely due to the difference in sensor trigger threshold, and not a cause for concern." The Ruina panel also acknowledged the near identical nature of the first pulse, not to mention its strong resemblance to past nuclear explosions.

Even so, there is still a notable difference in the shape of the first pulse for the two events in Figure 2. The French explosion has a faster rise time than Alert 747, although both are still a fraction of a millisecond. This is discussed in more detail later in the context of a nuclear explosion model of Alert 747 posited by the U.S. nuclear weapon laboratories. Further, there is a divergence in shape for the second pulse for both events. This is crucially important, as it was this difference that formed the major objection of the Ruina panel in considering the likelihood of Alert 747 being the signature of a nuclear explosion. But its presence in another confirmed explosion is revealing. The only difference between the two cases is the time at which this YCA vs. YVA divergence begins. In the French case, beginning at ≥ 100 ms, it is almost certainly caused by so-called 'tail-up' background modulation, to be revisited in a later section.[14]

Figure 2 also includes yield estimates for Alert 747 based on empirical scaling relations using the time of the intensity minimum between both flashes (5 ms) and the time of the second maximum (53 ms).[15] These scaling relations almost certainly apply to atmospheric explosions below about 30 km altitude. SSM80 notes that there is a modification for surface bursts and that the time of the second maximum is a less well-defined function of yield for yields less than about 100 kt.[16]

As the above demonstrates, reasonable sense can be made of the available double-flash data using empirical relations to derive a yield. But the data could only be modeled and properly understood in its entirety by using radiation hydrodynamics, the relevant physics of which is highly complex, especially given the time-dependent nature of the hydrodynamic expansion phase of the explosion. Applicable radiation hydrodynamics computer codes are not readily available and almost certainly not immediately useable for a non-expert. Nor are they easily constructed. Details are scarce, but modeling of the Vela incident was performed in several works using a code called RADFLO.[17] Codes such as RADFLO require data on material properties, such as opacities and equations of state, at extremely high temperatures and pressure, information that is also not readily available (e.g., for fissile materials).[18] They may also require specific nuclear weapon design parameters to reliably match a prediction with data (for example, the rise time of the first pulse), information that is obviously not available to the general academic community.

The Ruina panel's assessment

The Ruina panel was appointed in October 1979 by the U.S. Presidential Science Advisor Frank Press to analyze the Vela incident. The panel reported its conclusions to the U.S. government in May 1980 and a declassified version became available a few weeks later. Though still considering a nuclear explosion to be possible, the panel favored a natural explanation, stating that "although the panel is not able to compute the likelihood of the September 22, 1979 event being a nuclear explosion, based on our experience in related scientific assessments, it is our collective judgment that the September 22 signal was probably not from a nuclear explosion."[19]

Several additional reports on Alert 747 have been published by scientists with direct day-to-day involvement in designing nuclear test detection equipment and/or in analyzing data from the relevant instruments and comparing these data with data from U.S. nuclear weapon tests. They contain sufficient detail to compare them directly to the Ruina panel's conclusions (e.g., OJ80, Ma80, Ho80, SSM80).

Overall, there is a disparity in conclusions made by different sets of people based on the same data. There is also insufficient original data available for a non-expert to adequately model all relevant aspects of a nuclear explosion scenario for Alert 747. Further data are unlikely to become available for either the Vela incident itself or comparison events for benchmarking purposes. Against this backdrop, to shed new light on the Vela Incident, the following analysis approaches the problem from multiple but complementary technical perspectives. It includes a new assessment of the state of the Vela 6911 satellite in September 1979, a comparison of the Alert 747 signal to both the Vela zoo-ons and other nuclear tests, and an assessment of the physics of proposed alternative(s) and thus judging their (un)likelihood. In a separate paper, to be published in a subsequent volume of this journal, potentially corroborating radionuclide and hydroacoustic evidence is examined to determine whether the alert could have originated from an unrelated source.

Alert 747 bhangmeter readings—similarities and differences

Both bhangmeters on Vela 6911 detected the double flash, but the shapes of the intensity-time curves were slightly different. As already mentioned, after accounting for well-known and characterized instrumental effects, the signals of the two bhangmeters through the first maximum of the pulse were in excellent agreement (SSM80, Ma80). This is significant as the fast rise time of the first pulse is diagnostic of a nuclear detonation, and the Ruina panel notes that "the three separate yield determinations, which are normally derived from the time of the maximum and minimum of the pulse shape, are in rough agreement," i.e., to a similar level as past low-yield events. These three yield determinations would have been based on the time of the minimum, the time of second maximum, and (probably) "the time after minimum at which the 'well' in the irradiance-time curve is a factor of 3 wide in time" (so-called 3T, SSM80). Further, the integrated energy should be consistent with these estimates. The panel's statement can be read as stating that both the intensity and temporal behavior of Alert 747, from both bhangmeters, closely mimicked that of an atmospheric nuclear blast.

The two optical sensors, however, displayed different (relative) amplitudes of the second maximum, above and beyond the 5 LD units expected from their different sensitivities. According to SSM80, the more sensitive YCA bhangmeter looked like an airburst since the second peak was higher than the first, whereas the less sensitive YVA bhangmeter looked like a surface burst since the peaks had more similar amplitudes. This phenomenon can be observed in Figure 2, which compares Alert 747 to a French atmospheric test.

The bhangmeter difference was elegantly demonstrated in Ru80 by a plot of the Alert 747 YCA and YVA signals against each other, together with those of 12 previous nuclear detonations recorded by the Vela 6911 satellite. In the words of the panel: "If at one time the bhangmeters recorded YC = 20, YV = 10 on a linear scale, then at a later time of YC = 20 again, one expects to see YV = 10 again, although YC may not be twice YV for other values. A 'scatter plot' in which amplitude readings for the two bhangmeters are plotted against each other, should show a narrow locus for the recorded signals." Indeed, the entire first pulse of Alert 747 was fully consistent with past nuclear tests, a crucially important point and indicative of the source being located far from the sensors. On the other hand, the second pulse followed a different locus, suggestive of the source being close to the sensors. It is of critical importance to note, however, that the 12 other loci had been truncated at the onset of background modulation (so-called tail-up or tail-down to be discussed later). Though an onset time was not provided, it would typically be ≥ 100 ms. Thus, the second pulse loci of some or even all the 12 other explosions were either incomplete or not plotted (for megaton-class events), and the overall comparison inconclusive. The statement by the Ruina panel that "such anomalous [sic] behavior was never observed in bhangmeter recordings of previous nuclear explosions" lacked this important caveat. What if background modulation started earlier for Alert 747? Or had an otherwise abnormal shape to its temporal behavior? These are questions revisited in a later section.

Also highly significant, Ma80 states that, due to a malfunction of the spacecraft memory in July 1972, the last nuclear detonation recorded by Vela 6911 over its full time history occurred in June 1972, i.e., seven years before Alert 747.[20] The malfunction was such that it resulted in the loss of the second half of the bhangmeter time-history samples for all atmospheric nuclear tests, which would be everything after about 30 ms according to Table 1 in Ma80. As Figure 2 shows most of the second pulse would thus have been lost for tests with yields above about 1 kt, and the entire second pulse would have been lost for yields above 100 kt. There were five Chinese and 15 French atmospheric tests during the period up until March 1978 when Ma80 says the anomaly "cleared itself", though not all would necessarily have been detected by Vela 6911. Only a single confirmed explosion was detected by Vela 6911 after this time and up to the date of the Ma80 report, but the yield was so low that the less sensitive YVA didn't trigger and a comparison of the detectors was therefore impossible.[21] Only a single atmospheric nuclear explosion occurred after the Vela Incident. Conducted by China on 16 October 1980 with a yield of 0.7 Mt, it post-dates the Alert 747 reports, and it has not been made public whether this test was detected by Vela 6911. It would be of great interest to know if it was and whether the YCA and YVA traces showed a second-pulse anomaly like that of Alert 747.

The several-year loss of the second-pulse portion of Vela 6911 time histories is critically important because it is precisely the second half of the bhangmeter reading (in samples of logarithm of time) that is in question for Alert 747. For a period of more than seven years prior to Alert 747, there were no confirmed nuclear detonations detected by both Vela 6911 bhangmeters, rendering impossible a real "apples-to-apples" comparison to Alert 747. Having said that, both the on-board and ground-based laser calibration sources showed the bhangmeters to be operating nominally and consistent with pre-launch behavior.[22] But neither calibrator has the same time history as a real nuclear detonation, e.g., the laser pulse is a single peak of about a millisecond duration, and more importantly the background modulation is independent of the bhangmeter triggering process. The failure to mention the Vela 6911 memory loss was a significant oversight of the Ruina panel's report. If nothing else, it served to demonstrate that the satellite was not always in perfect working order, and that perhaps other systems had technical problems as well during its lifetime. This is revisited in a later section in a discussion of the background modulation.

Explanations for Alert 747 bhangmeter discrepancies

The difference in the second peak between the two bhangmeters was the crux of all arguments put forward against an atmospheric nuclear explosion as the origin for Alert 747. Specifically, the Ruina panel stated that, "although the September 22 event displays many of the characteristics of nuclear signals, it departs in an essential feature." The panel ruled out scenarios that involved normal or superbolt lightning, reflection off other satellites, or reflection from passing micrometeoroids, but it did not rule out other scenarios as possible explanations for Alert 747. The following subsections summarize a few of these candidate scenarios considered in the months following the event. In the process, an attempt is made to update the respective analyses using information that has become available since then from related areas of research.

The Vela Zoo

The Ruina panel's favored scenario was that the Alert 747 signal was a zoo-on, possibly originating from a micrometeoroid impact on the satellite. This event dislodged a "cloud" of tiny particles, which entered the view of the bhangmeters and reflected sunlight onto the detectors. Since each bhangmeter would have a slightly different field-of-view (FOV) at close range they would then display slightly different signatures.

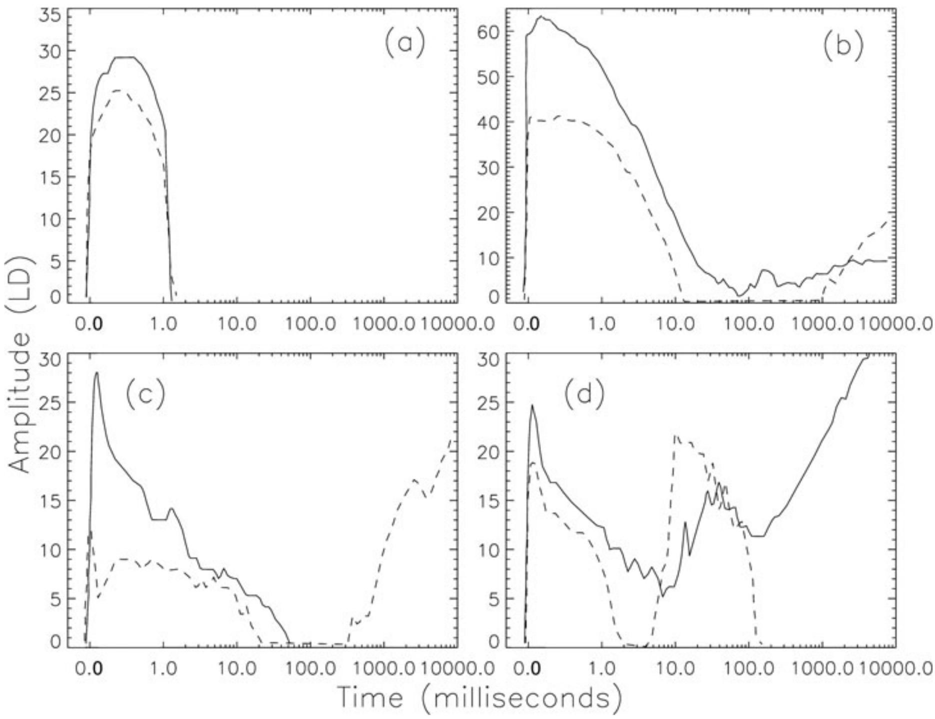

Figure 3. YCA (solid) and YVA (dashed) time histories of four Vela zoo-ons. Plots (a) and (b) are taken from OJ80 and were observed on 22 October 1971 and 5 November 1969, respectively. OJ80 identify them with reflection from a meteoroid passing through the bhangmeters' fields of view, almost certainly for the event shown in (a) and probably also for (b). Plots (c) and (d) are taken from Ru80 and were observed with the Vela 7033 satellite on 5 October 1973 and 10 September 1979, respectively. The Ruina panel suggested that these zoo-ons were possibly caused by debris passing the bhangmeters' fields of view after a meteoroid impact with the satellite. The increasing amplitude at late times is probably due to background modulation (see later section). Consistent with the originals, the time axis is semi-logarithmic, with the portion up to 1.0 ms being linear.

Even after decades of operating experience with the Vela satellites, the "zoo-population" was not a particularly large one. Available references list "about 70," "83," "a hundred," or "several hundred" cases out of hundreds of thousands of other non-nuclear triggers of the bhangmeters such as lightning and cosmic ray hits.[23] If a zoo-on, then Alert 747 was completely unique in several aspects. Some zoo events had features of the 1979 double flash but, as far as can be ascertained from the available reports, in no case did both bhangmeters display the classic double hump over the correct time and with the correct amplitudes to provide internally consistent inferred yields of a nuclear detonation.

Figure 3 contains plots of four zoo-ons, two published in OJ80 with data from an unknown Vela satellite, and two from Vela 7033 published in Ru80. Apparently, these are the only such data published for both bhangmeters of the Vela satellites. Similar plots have been presented elsewhere for five other "optical sensor readings of unknown origin," as they were described in one source.[24] Even though the originating satellite or date is not reported, the style of the plots (e.g., axis ranges and labels)

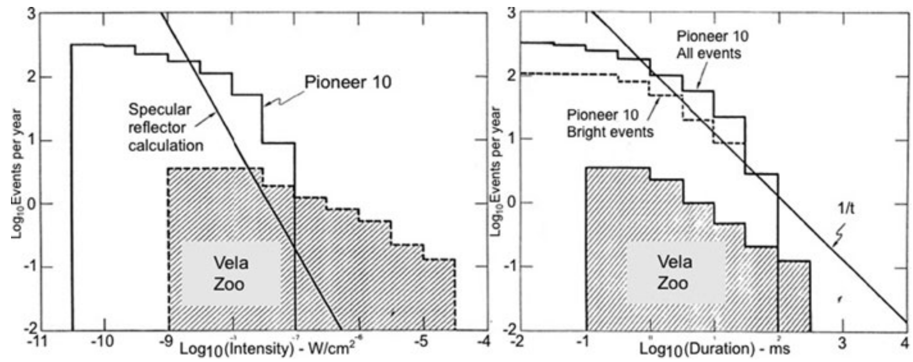

Figure 4. Reproduction of Figures 12 and 13 from OJ80, which shows on the left the cumulative $\log_{10}$(Intensity) and on the right $\log_{10}$(Duration) distributions, in $\log_{10}$ (Events per Year), for both the Vela zoo (shaded) and the Pioneer 10 Asteroid/Meteoroid optical detector. There were 83 Vela zoo events which satisfied the criteria set by OJ80 and which were taken from a sample period of 22.8 sensor-years. Also, only the 109 Pioneer 10 AMD events occurring over 124 days between 1 and 2 AU have been used. Respectively these imply about 3.64 and 320 events per year.

strongly suggests they are Vela-type, satellite-borne bhangmeter zoo-ons. These are discussed further in a following section.[25]

Prior to Alert 747, only one confirmed non-nuclear event had multiple pulses and a nuclear-like rise to first maximum (SSM80). This event was not considered a zoo member, however, because it was possible to explain the event by a known—though not identified—process. In fact, no other zoo-on ever had a first maximum that resembled the first maximum of a confirmed nuclear test (SSM80). Figures 3c and 3d highlight the sharpness of the first maximum for two zoo-ons compared to Alert 747 and the French explosion shown in Figure 2. Moreover, as a possible zoo-on, Alert 747 had other "very unusual PROPERTIES" (OJ80). These features not only include an exceptionally slow rise time compared to other zoo-ons shown in Figure 3 (see also Alert 747 in Figure 2) but also the presence of two temporally separate pulses (a "few" amongst "several hundred" zoo-ons according to Ru80) and atypical amplitude and duration. Moreover, a histogram of Vela zoo events versus duration shows that no zoo-on had a duration of more than about 300 ms (Figure 4, right hand panel). This is unlike Alert 747, whose duration was reported by OJ80 to be 380 ms.

Further, OJ80 state that for the zoo-ons "it is the exception, rather than the rule, for the two channels [bhangmeters] to provide consistent data," and that in many (perhaps most) cases it was not easily recognized that they even contained related data. While there is an obvious similarity between the YCA and YVA readings for the single pulse events in Plots (a) and (b) of Figure 3, this is not as clear in Plot (d) and even less so in Plot (c). Unlike the first pulse of Alert 747, in no case would a plot of YCA against YVA follow the locus of nuclear explosions provided in Ru80.

OJ80 note that the probability of these differences between the zoo-on population and Alert 747 occurring simultaneously could be estimated from the zoo-on database, but did not do so. One could however approach such a calculation from a simple direction if these differences are independent, i.e., not correlated. For a zoo-on population of about 100, one could then estimate the probability of an event having an intensity between $10^{-8.5}$ and $10^{-7.5}$ W/cm^2, i.e., bracketing the value for Alert 747 of 10^{-8} W/cm^2 and a total duration of more than 100 ms. To assist in the calculation, Figure 4 shows CUMULATIVE histograms of the Vela zoo-on count as functions of intensity and duration; they are plotted along with Pioneer 10 data (reasons for which will become clear later). The histograms show that there are about 39 zoo-ons with intensity less than $10^{-7.5}$ W/cm^2, and 3 zoo-ons with duration longer than 100 ms. From a sample of 83 zoo events occurring over 22.8 sensor-years their combined probability is thus only 0.017 even with this quite general set of properties. As a corollary this might be expected to occur once in every 5000 events (or almost 1400 sensor-years). Assuming no biases in the system and/or that other more specific properties are independent, such as a nuclear-like rise time, two pulses and internally consistent minimum and second maximum times, which are either unprecedented or highly unusual within the zoo population, then it can be seen that the probability of finding all these properties together in a single zoo case becomes ever smaller.

Another study concluded that a significant number of zoo events, particularly those triggering only one bhangmeter, could be explained as energetic particle hits.[26] A smaller number had signatures that could plausibly be created by reflection from a small meteoroid passing through the FOV of the sensors.[27] None of the remaining events had the characteristic features of a nuclear detonation. It was instead found that the bhangmeter difference of Alert 747 could have been created by a background modulation enhancement—a result of spacecraft system aging—of the much longer second maximum portion of the time history of the YCA bhangmeter. This possibility will be further discussed in a later section.

It is curious that the Ruina panel chose to show zoo-ons not from Vela 6911 but from Vela 7033 instead. Perhaps this was due to the loss of the second half of the bhangmeter readings on Vela 6911 from July 1972 through March 1978. If it is presumed that the two featured examples are the ones that look most like Alert 747, i.e., Plots (c) and (d) in Figure 3, then they must be the best of a very bad lot in the zoo-on population. Comparison of those signals to the Alert 747 signal in Figure 2 shows that they are very different. Whereas the fast rise and sharp first peak are common for the YCA and YVA bhangmeters in Plots (c) and (d), their subsequent shapes are markedly dissimilar to each other, including highly discrepant second maximum times in Plot (d).[28]

Micrometeoroid collision and one or two debris particles

One of the studies commissioned after Alert 747 examined single-object scenarios to reproduce both bhangmeter readings, without invoking a technical fault or spurious background issue for either.[29] For the class of objects that could produce plausible YC and YV time histories, there were numerous strict constraints on both the properties and trajectories of the debris object. For instance, given that the first pulses are nearly identical both in shape and amplitude, an object must not trigger the bhangmeters immediately upon entering the FOV; instead, triggering must be delayed until the object was close to the center of the FOV of the bhangmeters. The relative sensitivities of the sensors are quasi identical up to an off-axis angle of 6 degrees, but then diverge sharply and drop by a factor 10 at about 10 and 15 degrees, respectively for YV and YC.[30] To produce a signal consistent with Alert 747, the object would have to be in the FOV for a significant time before trigger. Since the separation of the two sensors was about 30 cm, the object had to be more than 1.5 m away from the detectors during the first pulse; and, based on the position of the sun along with geometric optics arguments, the object had to be closer than 30 m to produce the second pulse and their difference.[31]

The lack of fine structure in the pulse shape implies that the object had to be rotating quite slowly, only a few revolutions per second. The object must have moved with a velocity of less than 10 m/s through the FOV, which almost certainly restricted the object to be a piece of the satellite itself, perhaps ejected by a micrometeoroid collision. The relative velocity of the vast majority of micrometeoroids at the 110,000 km orbital radius of Vela 6911 would be no less than about 0.8 km/s, dictated by the conversion of gravitational potential energy to kinetic energy when brought from infinity.[32] Indeed, observations of meteorite velocities at similar distances to Earth show them to be several km/s and upwards.[33]

Notwithstanding that it would be virtually impossible for a high-speed collision to produce just a single debris particle, the above-mentioned restrictions necessitated a highly specular reflection from a facet (a flat face on a geometric shape).[34] This was required to allow the particle to be in the FOV without triggering the bhangmeters, but then to produce a glint as it rotated and caught the sun. With a fast rise and duration of around a millisecond the glint could feasibly mimic a nuclear-like first pulse. But the particle and its translational and rotational motion had to be tailored very specifically to exactly produce a nuclear explosion signal. To reproduce the rest of the bhangmeter trace, e.g., the second maximum, required attaching a second object, which bore no relation to the glinting facet object and had completely different surface properties. Such objects were considered to be too highly contrived.[35]

Instead, both bhangmeter readings could be reproduced with a single truncated sphere, starting at about 2.15 m from the satellite, moving away at 1 m/s and rotating about two axes at around 2.5 radians per second each. Further, it had to be about 1 mm in size, and the facet producing the first maximum about 5 microns across. With these assumptions, plus a restriction on the surface properties requiring a smudge to reduce the first maximum of one bhangmeter or a focusing area to brighten the second maximum of the other bhangmeter, the likelihood of finding such an object in the immediate vicinity of the satellite was considered to be extremely remote.[36] The natural speed of an object spun off the satellite was 0.1 m/s in the wrong direction, so its velocity would have to be increased by a factor of 10 and brought around the satellite in such a way as to pass through the respective bhangmeter FOVs and become visible in a specific way to the detectors.

Ultimately, the problem reduced to the difficulty of conceiving a mechanism that would drive a locally generated and highly specific particle into the correct trajectory. A single particle origin for the Event 747 signal was "conceivable, but so improbable as to stress reason."[37] From statistical considerations it was found that the volume of material lost by Vela 6911, before an ejected piece goes in the right direction on its first pass to produce the bhangmeter traces, was more than the entire satellite volume itself. For a later pass, all or most of the exposed surface area would have to be eroded. These are powerful arguments against a single-object scenario.

Another attempt to match the Alert 747 time history used two objects, one to produce each peak.[38] The objects were flat plates sufficiently small to be regarded as point sources and behaving as Lambert's Law radiators, which exhibit the same apparent brightness from any angle. The YC time history could be reproduced to within a factor of two if the plates moved parallel to the bhangmeter optical axis with specific velocities and spacing to produce the first and second pulses. But the YV reading could not be reproduced simultaneously regardless of how the plates moved within the sensor FOVs. A similar result was found for a two-meteoroid scenario. In this case, the meteoroids would have to pass Vela 6911 within some 10 ms of each other, which was estimated to occur only once every one billion (10^9) years.[39]

Ultimately, despite significant efforts in the year following Alert 747, no viable scenario involving one or two objects could be identified. This led the Ruina panel to suggest an alternative scenario—one that remains untested to this day.

Micrometeoroid collision and multiple debris particles

The Vela 6911 satellite is a 26-sided polyhedron, with 24 sides comprising solar panels (Figure 5). The other two sides point toward and away from Earth, the former containing the two bhangmeters.[40] The shape of these two sides is hexagonal, so there are six solar panels neighboring it, each of which is a trapezium.

It has not been possible to find a schematic of the satellite structure in the literature, only photographs and/or artist impression drawings, none with a scale bar. Although it is known that the spacecraft was about 1.2 m across, precise dimensions and angles are difficult to estimate.[41] The somewhat "squat" nature of the spacecraft suggests that the planes defined by the hexagonal segments, in one of which the two bhangmeters are mounted, and the six neighboring sides are inclined at around 30 degrees to each other (Figure 6).

Unfortunately, no report is available on the micrometeoroid impact scenario, in which multiple objects, either ejecta from the satellite or debris of the micrometeoroid itself, were modeled. As stated by the Ruina panel, the model appeared to propose that a collision of a micrometeoroid on the exterior surface of the spacecraft could produce the Alert 747 time history. It was under-developed at the time of the Ruina panel report, but quoting almost verbatim the short initial pulse arose from the entry of the first or first several [presumably faster moving] particles from the ejecta into the field of view, and the longer duration second-pulse from THE [presumably slower moving] large mass of ejecta that would soon follow. This does bear some similarity to real events in the laboratory, i.e., separate sets of debris

Figure 5. An impression of the Vela 6911 satellite in orbit above Earth. Of the 26 sides, 24 are covered in solar panels to provide power to the spacecraft. White projections on the underside are the ends of the bhangmeter sunshades pointing toward Earth, which is also the spacecraft spin axis. Other radiation sensors at the apex (intersection) of multiple panels point toward space to detect exoatmospheric nuclear detonations, exoatmospheric nuclear detonations. Photo credit: NASA Goddard Space Flight Center.

moving along broadly similar trajectories but at different velocities. As summarized below and detailed in the online supplementary material, the collision scenario has many shortfalls, however.

The expected collision speeds of several kilometers per second constitute so-called hypervelocity impact (HVI). A solar panel is the most likely surface to be hit by a micrometeoroid because these panels cover the bulk of the satellite surface area. As shown in Figure 6, the geometry of the satellite also strongly suggests that for collisional debris to promptly enter the FOV of the bhangmeters, the colliding particle must strike one of the six neighboring solar panels. Assuming an isotropic distribution of incoming trajectories, the statistical likelihood of a collision scenario being the explanation for Alert 747 is already reduced by a factor of around 6/24, i.e., a quarter. Here it is assumed that all 24 solar panels have an approximately equal area. So the problem is no longer ‘merely’ a hit to the satellite but instead a hit to a particular part of the satellite.

In HVI the major debris components are called spall and cone; they are depicted in Figure 6 and discussed in more detail in the online supplementary material. The relative proportions of spall and cone ejecta generated upon impact depend on the type of surface material, broadly categorized into ductile and brittle. Most metals are ductile, whereas materials commonly used for solar panels are brittle. Spall contains most of the ejected mass for collisions on

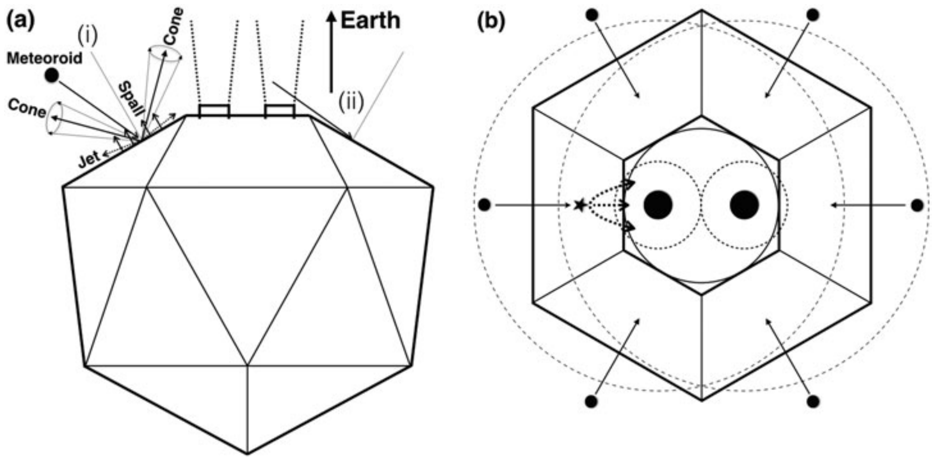

Figure 6. Simplified side-view (a) and top-view (b) sketches of the collisional geometry between a meteoroid and the Vela 6911 satellite. In (a), the two bhangmeters are represented with their respective FOVs pointing in the direction of the Earth. The FOVs are drawn at 6 degrees off-axis, the angle up to which their response profiles remain similar, with a relative sensitivity between about 0.8 and 1.0 (SSM80). Relative sensitivities drop to less than 0.1 at 10 degrees and at 15 degrees for YV and YC, respectively. Only a collision on one of six panels neighboring the bhangmeter plane can possibly produce promptly detected debris. In (b), the two large filled circles represent the bhangmeters pointing out of the page.[42] The inner and outer dashed circles are their FOVs at heights of around 1.5 m and 6 m, respectively. Below 1.5 m, the FOVs do not overlap anywhere, and particles traveling on most trajectories would not be detected by both sensors, except those close to the axis connecting them. Meteoroids are shown approaching each of the six panels closest to the bhangmeters, though for clarity only one shows possible impact debris directions, in this case for a grazing or glancing collision. See text and online supplementary material for further details.

brittle material (up to 90%), is always ejected at 90 degrees to the plane of the surface, consists of a relatively small number of particles, and is the last and slowest of the ejecta.[43]

For HVI on one of the six solar panels adjacent to the Vela 6911 bhangmeter plane, the cone debris can in principle enter the FOVs, but several difficulties arise for it to be responsible for the first pulse. These are described in detail in the online material. The spall debris constitutes the bulk of the total debris mass, but for a collision on any part of the six solar panels neighboring the bhangmeters, the spall moves away from the FOVs as can be verified in Figures 5 and 6. For most of the surface area of those six panels, the spall would never even enter the FOVs, and there would be no second pulse at all.

Summarizing the considerations detailed in the online supplementary material, the following conclusions can be drawn. First, the construction (geometry) of the Vela 6911 satellite itself provides a very good protection against collisional debris entering the bhangmeter FOVs from most of its surface area. Only a collision on the six closest solar panels could in principle send debris into the FOVs. Second, the physics of HVI on solar panels dictates that the bulk of the ejected mass is contained in relatively large spall particles, which move normal to the surface and thus away from the FOVs. Third, high cone elevation angles could send debris into the FOVs but, even if triggered, the sensors would likely show only a moderately steep rise and then a slowly decaying signal, rather than a double pulse. Fourth, low cone elevation angles or ricochet from a glancing collision could trigger the bhangmeters, but the debris would pass less than 1.5 m above them, thus being inconsistent with the near identical observed first pulses of Alert 747. And fifth, given the first pulse of Alert 747 must come from faster moving material because it appears first and lasts only a few milliseconds, the signal is most consistent with cone ejecta properties. However, cone ejecta does not consist of just one or a few particles, as was proposed by the Ruina panel to produce the first pulse rather hundreds or thousands of particles are created, and there is no obvious mechanism for them to be sufficiently separate, temporally or spatially, to produce a double pulse.

These considerations severely constrain the possible trajectories of an incoming meteoroid that might produce a signal on the bhangmeters, let alone one that has two pulses and mimics a nuclear explosion. It is even more difficult to construct a scenario in which one or several particles enter the FOVs first to be then followed by a debris cloud, as the Ruina panel postulates. The Ruina panel did not consider it their role to establish the meteoroid collision—or any other non-nuclear—scenario as the explanation behind the anomalous bhangmeter readings of THE Alert 747 SECOND PULSE, but the discussion here argues strongly against it.

To further support the assessment that a collision was unlikely to have produced the Alert 747 signal, data from the Asteroid/Meteoroid Detector (AMD, also known as Sisyphus) on the Pioneer 10 and 11 interplanetary probes are now discussed. The Ruina panel used AMD results to support the collision model, assuming Alert 747 was a Vela zoo-on, but the argument bordered on being circular, claiming that each data set supported the other but in the absence of an explanation for either.

Vela and the Pioneer 10/11 AMD

One of the problems in 1979/1980 in assessing the micrometeoroid impact model, which required the production of one or more secondary particles, was the lack of related data from other spacecraft with light-detection instruments. The only relevant database existing at the time was from the Pioneer 10 and Pioneer 11 spacecraft, which were both equipped with optical and impact detectors, the AMD and the MDE (Meteoroid Detection Experiment).[44] The AMD had two operational modes, zodiacal light and individual particle, the latter being the one discussed here unless otherwise noted. Consisting of four 20-cm aperture telescopes each with a 7.5 degree FOV, their own detection system, and with approximately parallel optical axes, the purpose of the AMD was to use the passage of a meteoroid to derive orbital parameters.

According to the Ruina panel, the AMD triggered about a hundred times more frequently than the MDE, a result that was controversial at the time and remains unexplained to this day. In no case could an orbit be derived. The Pioneer AMD vs MDE discrepancy was used by the Ruina panel to support their model of a collisional debris cloud for Alert 747. While not explicitly stated, their assumption was probably that a sufficiently small meteoroid would not be detectable by the MDE since it relied on penetration of 25 and 50 μm thick stainless-steel panels on Pioneers 10 and 11, respectively. This corresponds to minimum particle masses of 8.3×10^{-10} g and 6.0×10^{-9} g (or radii of about 7.3 μm and 14.2 μm, assuming a density of 0.5 g/cm^3) and an impact velocity of 20 km/s.[45] On the other hand, if a meteoroid of comparable or even smaller size impacted elsewhere on the spacecraft, then solar reflection off its debris particles, which is proportional to the total surface area of the debris, would be much greater than reflection off the original body and thus could trigger the AMD. That such supposed collisions occurred more frequently than MDE penetrations could be explained by both the greater surface area offered by the entire spacecraft and by the fact that for most cosmic dust size distributions (interplanetary as well as interstellar) the smaller particles outnumber the larger ones. Using models for the interplanetary dust distribution that have been constrained by modern observations, and assuming similar detecting surface areas, the AMD would need to have detected collisional debris from grains five orders of magnitude lighter than the MDE for it to see a rate 100-times higher.[46]

The Ruina panel did not mention several highly relevant aspects about the AMD, and its differences to Vela, that would help assess the relationship between the two experiments. Some of these aspects are described in OJ80 and elsewhere in the scientific literature, and they are discussed in detail in the online supplementary material. There it is shown that serious questions remain over the reliability (even reality) of the AMD data. The AMD results cannot be explained by models of the interplanetary dust population, which have been constrained by many other and more modern observations. Nor do the technical specifications of the AMD allow a thorough comparison to the Vela zoo-ons. Overall, AMD data does not provide a reliable template against which to compare the Vela zoo-on signals and especially Alert 747.

Background modulation

As previously noted, Ma80 suggests that the time history of YC's second pulse may have been disturbed by an abnormal background modulation. This is where the eight-year memory loss of the second maximum component becomes significant because it precludes a comparison of Alert 747 with another confirmed nuclear explosion from around the same time. The satellite was operating beyond its design lifetime, the failure of its EMP sensor being a symptom of its advanced age,[47] but other age-related problems could have been inherent to the system at that time. Post-event tests did find that the background behavior was different compared to earlier on-orbit years, including higher frequency, large amplitude modulation signals, as well as earlier than expected "tail-up."

Tail-up (or tail-down) was common to all Vela nuclear explosion signals, a consequence of background compensation being inhibited once the bhangmeters were triggered. The total signal was thus a sum of the real event plus background, with tail-up and tail-down denoting when the background was increasing or decreasing through the recording. This was modulated at the 64-second rotation period of

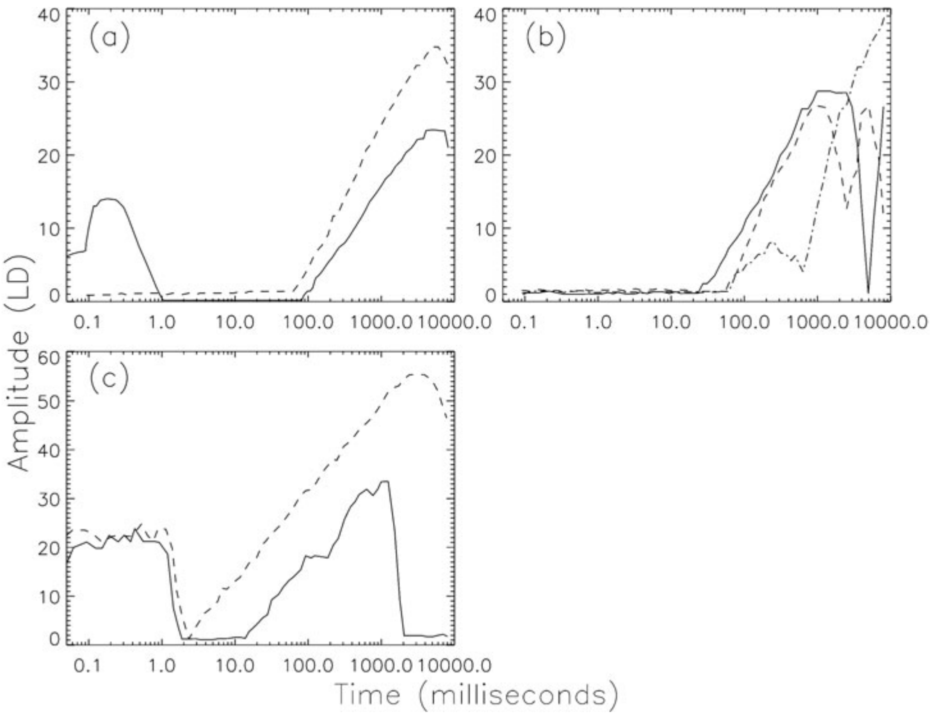

Figure 7. Example background modulation ("tail-up") time histories for the YCA bhangmeter on Vela 6911. Data in Plot (a) taken from Ru80 for "normal" tail-up after a lightning trigger on 26 October 1979 (solid) and Ma80 for a typical response on 19 November 1979 (dashed); data in Plot (b) taken from Ma80 for atypical responses on 17 November 1979 (solid), on 17 November 1979 (dashed), and on 21 November 1979 (dot-dashed); data in Plot (c) taken from Ma80 show atypical laser calibration responses, both taken on 27 November 1979. Unlike the light curves in Figures 2 and 3, the time axis is logarithmic across its entire extent, except for the lightning case in Plot (a), whose axis should be read as linear up to 1.0 ms, i.e, 0.1 ms corresponds to 0.0 ms.

the satellite. This effect can be seen in Figure 2 for the French atmospheric nuclear explosion. Following the second maximum, the YCA response first drops steeply (as it should), but then the slope decreases considerably at around 300 ms.

Given that the magnitude of the YCA tail-up was consistently—on a statistical basis—larger than the YVA tail-up, Ma80 suggests that "it could likely be the cause of the YCA-YVA difference signal" for Alert 747. Notably, according to Ho80 both sensors were receiving background light from the crescent Earth at event time, as well as sunlight reflected from those surfaces directly illuminated by the Sun. They further note that the background irradiance was a few orders of magnitude larger than the signal's maximum irradiance. Ma80 conclude (or speculate) that if the Vela 6911 traces were corrected for this background effect, then the Alert 747 signal would be fully consistent with expectation from a low-yield atmospheric nuclear detonation.

Figure 7 shows the range of background modulation signals seen by the YCA bhangmeter for Vela 6911 as given in Ma80. In Plot (a), the tail-up signature is also shown following a lightning trigger, with a duration of about a millisecond. Notably, both examples of Plot (a) start at around 60–100 milliseconds and have a monotonic increase, likely induced by the spacecraft rotation period of 64 seconds. On the other hand, the signals in Plot (b) either start slightly earlier or are no longer monotonic, but instead contain specific features. These are incompatible with spacecraft rotation and may arise from vibrations due to wear on the reaction wheel bearings. In Plot (c), the bhangmeter has been triggered by a ground-based laser calibration, with a signal duration of about one millisecond. In this case, the background signal begins to increase even sooner, in one case as early as 2 ms after the trigger event.

The Ruina panel report does mention the background issue in the context of spurious reflections from the detector baffles, which had been presented late in their meetings. The panel noted that such a possibility should be pursued but, without further justification, decided it was unlikely to be the cause of the YCA-YVA discrepancy. This conclusion may have been reached because the plot of YCA vs YVA signal was "truncated at the onset of tail-up or tail-down effects," and the panel assumed that this adequately accounted for background. When truncating the signals, however, it may have been assumed that the onset time was common for all events, probably around 100 ms as shown for a typical background modulation, as well as a lightning case (Figure 7a). Yet, as also shown, several post-event tests showed tail-up beginning much earlier, e.g. around 10–20 ms and even as early as 2 ms (Figures 7b and 7c). Obviously, such an atypical background modulation response could significantly perturb the second pulse portion of a nuclear explosion signal, above and beyond what might be expected based on earlier explosions. In this context, it is again worth pointing out that Vela 6911 had not observed a full time history of a confirmed nuclear explosion since mid-1972. Overall, the panel's conclusion to reject background modulation as a possible explanation for the bhangmeter discrepancy during THE Alert 747 SECOND PULSE appears premature today.

An ultimate explanation for (some of) the Vela zoo?

The Ruina panel and others were confident that certain types of events can be excluded from consideration as potential origins for either the Vela zoo or Alert 747. Normal or superbolt lightning did not produce the zoo-ons or Alert 747, and Alert 747 was not a result of solar reflection off a passing meteoroid, distant satellite, or an object somehow spun off Vela itself. A bolide entry into the Earth's atmosphere can also be ruled out, as explained in the online supplementary material.

Hypervelocity impact on sunshade interior surface of bhangmeter itself?

One of the most obvious differences between the Alert 747 signal and that of the two zoo-ons from Ru80 in Figure 3c and 3d is in the first pulse. While the slower rise time of Alert 747 compared to zoo-ons had already been mentioned by others, e.g., OJ80, another feature is the shape of the peak itself. Zoo-ons tend to rise extremely rapidly to the peak, turn over sharply and initially decrease rapidly as well, but then change slope and decrease much more slowly.

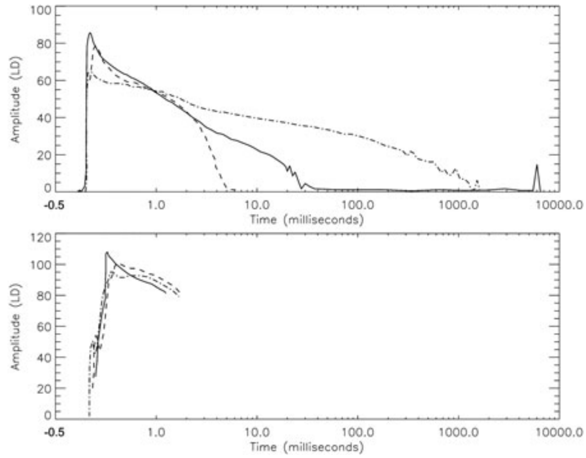

Figure 8. In the upper panel are time histories (or light curves) of three optical signals of unknown origin recorded by in-orbit bhangmeters on unidentified spacecraft (though probably not Vela). Note the similarity in rise time and shape of the peak region to those of the Vela zoo-ons in Figures 3c and 3d. The bottom panel contains the time histories from ground-based experiments of particle impacts on the interior surface of bhangmeter sunshades. Different levels of ambient lighting have been applied, from darkness to full illumination to simulate scenarios without and with solar scattering off debris. As for Figures 2 and 3 the time axis is semi-logarithmic, with the portion up to 1.0 ms being linear.

This characteristic feature is also seen in signals detected by other satellite-borne bhangmeters and presented by teams from two U.S. government laboratories, namely the Department of Energy's Sandia National Laboratory and the Air Force's Phillips Laboratory. They were called "anomalous optical sensor responses" and "optical sensor readings of unknown origin."[48] They are almost certainly a manifestation of Vela-type zoo-ons but seen from different spacecraft, possibly the Global Positioning System (GPS) and/or DSP satellites previously mentioned. One team suggests that three satellite platforms and five different bhangmeter designs were involved. Some of these signals are reproduced here in the upper panel of Figure 8, since they were plotted by the authors in the same style as in Ru80 (for the others no units were provided for the time axis, nor whether it is logarithmic, thus making it difficult to compare "shape-for-shape" with the Vela zoo-ons).

It was pointed out by the Sandia team that in the mid-1990s an explanation was put forward that proposed that the signals could be the impact flash of a meteoroid hitting the interior surface of the bhangmeter sunshade.[49] Although neither the original report nor any rebuttals were published, apparently the idea was dismissed, the argument being that the flash would not be sufficiently bright to trigger the sensor. Thus, a modification was suggested in which the light was supplemented by solar scattering from debris.

To test the impact flash idea both the Sandia and Phillips teams performed a series of HVI experiments on either bhangmeter sunshade material or an actual bhangmeter, with recording systems like those used on orbit. Two independent series of experiments complemented each other, using a different composition, mass, and velocity of the velocity of the COLLIDER particles. Using a Van De

Graaf accelerator the Phillips team fired iron projectiles with masses from 6.6×10^{-15} to 10^{-12} g to velocities ranging from 38.0 km/s to 7.6 km/s respectively, while Sandia used a two-stage gas gun to fire aluminum projectiles with a mass of a few micrograms and a velocity of about 7.3 km/s. The Phillips team also performed HVI experiments on the bhangmeter lens, as well as numerical calculations of four specific HVI cases, results of which compared well to the experiments with the same parameters of impactor mass, velocity and composition, and surface composition.

The results of the Sandia experiments are shown in the lower panel of Figure 8. The three cases are for a direct hit on the sunshade material in the dark (solid line), oblique impact on the interior surface of a sunshade and unintentionally semi-illuminated by light from the gas-gun entering the experiment chamber (dashed line), and oblique impact on interior surface of sunshade intentionally fully illuminated by a lamp (dot-dashed line). The latter case simulates the space environment of solar light scattering from debris.

There is a clear similarity in both the rise time and peak response shape between the on-orbit and laboratory signals. They strongly resemble each other, e.g., rise times of tens of microseconds for the on-orbit signals are consistent with the experiment.[50] Unfortunately, the experimental apparatus did not allow extension of the data to the longer times seen on orbit. But the Sandia team concluded that the slope of the amplitude decay is such that the sensor would detect a signal out to 10 ms for their line-of-sight case, and it is suggested here that a similar extrapolation out to even longer times applies for the other cases.

The relatively long decay of the on-orbit signals, compared to typical laboratory cases of impact flash,[51] is likely to be a result of two phenomena. One is the illumination of particulate debris by the Sun, the scenario seemingly favored by Sandia. The other is a multitude of secondary impact flashes merging together as debris from the initial collision strike other parts of the sunshade, the scenario seemingly favored by the Phillips team. Of course, both processes could occur, which would explain the few orders of magnitude discrepancy in the total light energy between the in-orbit and ground-based data.

While this does not necessarily constitute a proof that the Vela zoo-ons and other anomalous optical signals were produced by a meteoroid impact flash inside the bhangmeter sunshade augmented by secondary impact flashes and/or solar light scattering by debris particles, both groups concluded that their experiments support that hypothesis. The Phillips team also found that the observed event rate is consistent with the expected flux of meteoroids with a mass of 10^{-8} to 10^{-4} g (the event rate would be far higher than observed if smaller particles contribute to the phenomenon).

The obvious caveat in the case of Vela is that it could not—at least at first sight—explain why such a collision would trigger both bhangmeters. No good explanation for this can be offered here. The literature on the Vela satellites strongly suggests that the two sensors have separate sunshades (e.g. Figure 5), and each has its own independent triggering circuitry.[52] Yet for the zoo-ons in Figures 3c and 3d the characteristic fast rise time and peak response shape of an impact flash are seen in both the YCA and YVA light curves. Perhaps one possibility is that the impact-generated plasma from a collision inside one sunshade generated an electromagnetic field and/or wave that induced a signal in the electronics of the second sunshade.[53] Unfortunately some critical text and diagrams (Figures 10, 11 and 12) are redacted from Ma80 that might otherwise have allowed a more definitive statement and/or explanation. In this context, it is worth noting that the Phillips team observed that " … satellites with three sensors onboard have detected the anomalous signal simultaneously on two sensors …"[54]

A nuclear explosion model

Several studies conducted in the aftermath of Alert 747 using the one dimensional (spherically symmetrical) radiation transport-hydrodynamics code RADFLO have proposed models that explain the bhangmeter double pulse by a surface level burst of around 1–2 kt yield.[55] RADFLO was specifically designed to compute early fireball behavior for low-altitude nuclear bursts, and its primary role was to predict and model optical signals produced by those bursts. Before Alert 747, the code had been extensively benchmarked against other airbursts, from both the U.S. and French testing programs, including satellite bhangmeter data. RADFLO had also been extended to study the effects of a large amount of mass around the device compared to a point explosion (with a very high yield-to-mass ratio) modeled in earlier versions of the code. The most important influence was found to be a distortion of the power-time curve up to and around the first maximum. The times of minimum and second maximum were not affected.

SSM80 explain that a large effective weapon mass can theoretically cause the first maximum to be delayed if two conditions are met. First, the mass must be sufficiently large to contain most of the explosion energy in the weapon material, limiting energy leakage into the surrounding air as x-rays. This condition implies a mass that keeps the external temperature of the weapon material below 100 eV (i.e., 1.16 million Kelvin, about a factor of 10 less than for an "unshielded" device).[56] Second, the subsequent expansion of the weapon material into the air must be reasonably uniform and stable. As a caveat, SSM80 note that U.S. nuclear test data do not provide a very critical test of the theory relating first maximum time to device mass, as experimental evidence is not available for low-yield explosions.

All above-mentioned Alert 747 reports conclude that the relatively long rise time for the first peak compared to the French shot in Figure 2 is due to a large mass surrounding the device. SSM80 apparently attempted to fit the YCA and YVA light curves separately. Under the assumption that YCA provided an accurate representation of a nuclear burst, the authors find that fitting both YCA and YVA leads to an implausible but not impossible model of the source. On the other hand, if YVA provides the most reliable time history, a self-consistent picture of the source can be obtained.[57] They further note that other teams had also concluded that the YVA sensor data was the most reliable, which provides further evidence that YCA may have been compromised by an atypical background modulation.

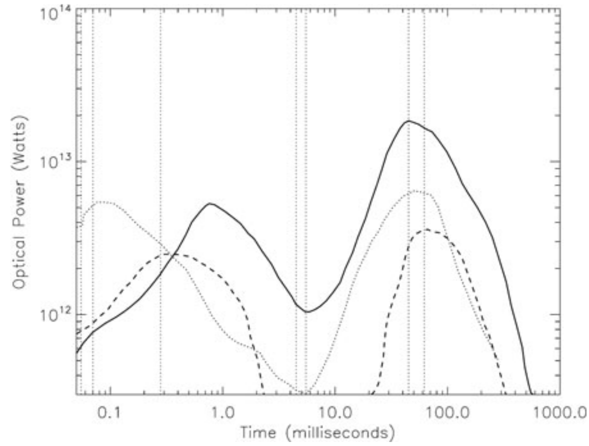

Figure 9. Plot of the Alert 747 YCA (solid) and YVA (dashed) time histories, expressed in optical power, along with a model for a 1-kt sea-level burst, though rescaled along the time axis to mimic a 2-kt burst (dotted curve). The time axis is logarithmic across its entire extent. The calibration of LD units to W/cm^2 (from OJ80) is only known for the YCA sensor; the same calibration has been applied to YVA even though, strictly speaking, their respective calibrations should be different and the same power should be seen by both sensors. Note the dotted line at about 0.3 ms, representing the time to first maximum of a 2-kt burst surrounded by a mass of 8000 kg. The maximum is delayed compared to a device with a mass of 100 kg, which has the maximum at 0.05–0.07 ms, and closely matches that of the YVA trace for Alert 747. The dotted lines around 5 and 50 ms represent times of minimum and second maximum, and do not change with device mass. See text for further details.

Unfortunately, none of the models in the Alert 747 reports is shown against the observed signal. The best that can be done is to take related models and plot them along with the Vela signal.[58] This is shown in Figure 9, where the observed data have been converted to optical power in Watts using the YCA calibration curve (Level Discriminator to W/cm^2) published in OJ80.[59] The model (dotted line) is the computed radiant power in the silicon band versus time for a 1 kiloton explosion of a device with mass 100 kg in sea level-density air and including non-equilibrium chemistry.[60] The curve has been rescaled by multiplying the time axis by a factor of 1.3, which corresponds to the average ratio of the respective time-to-minimum and time-to-second-maximum between 1 and 2 kt bursts.[61] The vertical dotted lines with small separation between each other represent t_{1max}, t_{min}, and t_{2max} for 1 and 2 kt explosions, using essentially the same model input parameters apart from a 30-kg difference for the device mass and without the inclusion of non-equilibrium chemistry. The other dotted line at just less than 0.3 ms shows the time to first maximum for a 2 kt burst but now surrounded by a mass of 8000 kg. It is clearly longer than is the case for a 130-kg device, and goes close to matching the data for Alert 747, especially the YVA trace. The times to minimum and second maximum are unaffected, and are also matched reasonably well for an explosive yield of around 2 kt. Notably, the approximately equal peak power levels in the first and second pulses are also common between the model and the YVA trace of Alert 747. No correction has been applied to the optical power from the 1 to 2 kt cases.

SEEMINGLY, there are differences in the time histories of YCA and YVA shown in Figure 9, and it's not possible to conclude which one is more accurate. However, as observed for example in Ma80, there is "excellent YCA/YVA signature consistency through the first maximum pulse portion of the Alert 747 data" once certain corrections are performed. Similarly, a plot of YCA versus YVA in Ru 80 shows that the first pulse of Alert 747 is consistent with twelve other nuclear explosions detected by Vela 6911.

Another caveat is that the mass surrounding the device is assumed to have the same equation of state as the air. This will not be the case, and the first pulse can be drastically altered if a more realistic equation of state, such as the one of water, is used for the surrounding material. In a 1-kt model surrounded by 100 tons of sea water, it was found that the first pulse disappears altogether.[62] Unfortunately, there are no details on the possible effects of a surrounding steel structure, such as a barge.

The combination of a surface burst and a large surrounding mass suggests a barge-like shot. Curiously, the panel did not compare the Alert 747 signal with the one from the 22-kt Arcturus test on a barge at Mururoa on 2 July 1967, even though it noted that "the bhangmeters on the Vela satellites have been triggered by and have recorded almost all previous nuclear explosions" in the atmosphere. Such a comparison could have provided valuable data on the impact of the barge and water mass just below the explosion on the optical signal. There were also three barge explosions in Polynesia in 1966, but the first launch of advanced Vela satellite pairs (Vela 7 and 8), the first with bhangmeters overlooking the Earth, took place on 28 April 1967, just two months before the last non-disputed near-water explosion on the planet.

Discussion and conclusions

The controversy over the origin of Alert 747 can be distilled down to asking what is the most likely of two alternatives: Was it a zoo-on, perhaps the signature of a meteoroid collision, either with the exterior surface of the satellite (debris model) or with the interior surface of the bhangmeter itself (impact-flash model)? Or was it instead the signature of a nuclear explosion, perturbed during its second pulse on the more sensitive bhangmeter by an early onset of (and/or otherwise anomalous) background modulation? Based on this new analysis, which included several recently declassified documents, the scenario of a meteoroid collision now appears much less likely. At the same time, the scenario of a nuclear explosion has gained enhanced credibility.

Accordingly, on 22 September 1979, Vela 6911 probably detected the characteristic and unique double-flash of a low-yield, low altitude, nuclear explosion. The evidence upon which this conclusion is based is supported by an independent and forensic technical analysis of all the information available on the public record. This includes Event 747 itself, the zoo-ons of both Vela and the Pioneers, the properties and history of Vela 6911, the physics of hypervelocity impact and laboratory experiments to simulate Vela and other satellite bhangmeter zoo-ons, and efforts to match the signal with nuclear explosion calculations.

In terms of the Ruina panel report, which came to the opposite conclusion, the following observations can be made:[63]

1) The panel did not mention the memory problem of Vela 6911, which lasted from July 1972 to March 1978 and resulted in the loss of the second half of all bhangmeter readings. As a result, there were no recent Vela 6911 detections of confirmed atmospheric nuclear explosions that could be directly compared to Alert 747. It is therefore difficult to judge the possibility of an aging spacecraft system having caused a perturbed detector signal.
2) The panel was premature in dismissing the possibility that the second pulse of the 747 signal was perturbed on the more sensitive bhangmeter by either an early onset or non-uniform background modulation. Both effects had been detected in on-orbit tests following the 747 signal. Indeed, perturbation by background modulation of the second pulse was a given for all other nuclear explosions previously detected by the Vela fleet, albeit of a consistent nature and post-trigger time.
3) The panel noted some similarities between the Alert 747 signal and the Vela zoo, but did not also mention some of their stark differences, such as the rise time and peak response shape of the first pulse and the total signal duration. No zoo-on had comparable first pulses from the two independent bhangmeters that showed such a degree of similarity with a nuclear explosion signal.
4) In using the Pioneer 10 optical meteoroid detector to support their collision scenario for Alert 747, the panel should have provided the caveat that the Pioneer 10 data were highly controversial within the interplanetary dust community, perhaps not even detecting real optical events.
5) The panel put forward an undeveloped model for a non-nuclear explanation of Alert 747, but did not mention that a nuclear explosion model had been developed independently by several groups, which explained the slower rise time of the first pulse compared to other airbursts.

While the Alert 747 signal had no precedence in the Vela zoo population, it cannot completely be ruled out as a statistical oddity. And an oddity it would indeed be given that its overall shape, in particular that of the first pulse, is manifestly different to the time histories of the two classes of zoo-ons so far identified. Instead, Alert 747 in both its signal shape and amplitude mimics almost perfectly that of a nuclear explosion, and the derived yield from up to four different (empirical) approaches are internally consistent.[64]

In a separate companion paper, to be published in the next issue, further evidence is presented that corroborate the conclusion that Vela 6911 detected a low-yield atmospheric nuclear detonation, probably over the southern Indian Ocean, on 22 September 1979. This evidence comprises a review of the available hydroacoustic data, as well as analysis of the short-lived fission product iodine-131 found in south-east Australian sheep thyroids in October and November 1979.

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Notes and References

1. A bhangmeter uses a silicon photodiode to record the temporal development of the irradiance of a transient event, as optical power per unit area. It is triggered to record when the incident irradiance and its rate of rise exceed pre-set levels. See G. H. Mauth, "Alert 747," RS 1243/80/12, Sandia National Laboratories, 1 May 1980, available at nsarchive.gwu.edu/NSAEBB/NSAEBB190.
2. France, China, Pakistan, and North Korea were not members of the treaty.
3. Several histories, of varying detail, have been published over the years; they include in particular: Jeffrey Richelson, *Spying on the bomb: American nuclear intelligence from Nazi Germany to Iran and North Korea*, (WW Norton & Company, 2007); Leonard Weiss, "Flash from the past: Why an apparent Israeli nuclear test in 1979 matters today," *Bulletin of the Atomic Scientists*, 2015, thebulletin.org/flash-past-why-apparent-israeli-nuclear-test-1979-matter-today8734 ; L. Weiss, "The Vela Event of 1979 (Or the Israeli Nuclear Test of 1979)," The Historical Dimensions of South Africa's Nuclear Weapons Program, 2012; L. Weiss, "The 1979 South Atlantic Flash: The Case for an Israeli Nuclear Test," in H. Sokolski (ed.), "Nuclear Nonproliferation: Moving Beyond Pretense: Preliminary Findings of NPEC's Project on Nuclear Nonproliferation Policy," Washington, DC, 2012, available at www.npolicy.org; L. Weiss, "Israel's 1979 Nuclear Test and the US Cover-Up," *Middle East Policy*, 18(2011): 83–95; David Albright and Corey Gay, "A Flash from the Past," *Bulletin of the Atomic Scientists*, 53(1997): 15–17.
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9. Guy E. Barasch, "Light flash produced by an atmospheric nuclear explosion," LASL-79-84, Los Alamos Scientific Laboratory, 1979, available at nsarchive.gwu.edu/NSAEBB/NSAEBB190.
10. Ibid.
11. Ruina et al., Ad Hoc Panel Report, op. cit.; Phillip J. Klass, "Clandestine nuclear test doubted," *Aviation Week & Space Technology*, 209(1980): 67–72.
12. Ruina et al., Ad Hoc Panel Report, op. cit.; Klass, "Clandestine nuclear test doubted," op. cit.; The Radiological Situation at the Atolls of Mururoa and Fangataufa, STI/PUB/1028, International Atomic Energy Agency, 1998; Barasch, Light flash produced by an atmospheric nuclear explosion, op. cit.
13. Mauth, Alert 747, op. cit.
14. Background comes from reflection of sunlight off the Earth itself, and possibly from adjacent satellite structures. This is usually suppressed electronically so that it does not trigger the bhangmeter, but once triggered, e.g., by an atmospheric nuclear detonation or even lightning, this suppression no longer occurs. Therefore, as the satellite rotates the background may modulate, increasing ("tail up") or decreasing ("tail down") during the recording of the transient optical signal (Mauth 1980, Alert 747, op. cit.).
15. Barasch, Light flash produced by an atmospheric nuclear explosion, op. cit.
16. Ibid.
17. Sappenfield, Sowle, McCartor, Possible Origins of Event 747 Optical Data, op. cit.; Horak, Vela Event Alert 747, op. cit.; E. M. Jones, R. W. Whitaker, H. G. Horak, and J. W. Kodis, "Low-Yield Nuclear Explosion Calculations: The 9/22/79 VELA Signal," LA-9062, Los Alamos National Laboratory, 1982.
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19. It is worth noting here what the Ruina report did not say, namely that Alert 747 was not the signature of a nuclear explosion. Shortly after the release of the report one of the panel members was quoted as saying that when the panel first convened they thought the chance that it was a nuclear explosion was 4:1 while at the end of their deliberations it was 4:1 against (Eliot Marshall, "Debate continues on the bomb that wasn't," *Science*, 209(1980): 572–573. Such odds are still quite reasonable.
20. This last nuclear detonation recorded over its full time history by both Vela 6911 bhangmeters was probably the French 4 kt Titania explosion on 30 June 1972 (and/or the 0.5 kt Umbriel explosion on 25 June 1972; there were no atmospheric tests by China during June 1972).
21. Based on the historical record, this must have been the 14 December 1978 Chinese test.
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26. Mauth, Alert 747, op. cit.
27. See also OJ80, where Plots (a) and (b) reproduced in Figure 3 are discussed.
28. Despite unavailability of the full suite of zoo-on light curves, this is already suggestive that they and Alert 747 arise from different physical processes. A similar point has been made previously, but from the position of a personal sighting in early 1981 of all the zoo-on time histories, and where it was noted that "there was not a single 'zoo animal' that came close to the classic shape in duration and amplitude." Leonard Weiss, "Flash from the past," op.cit. Also, a feature of the bhangmeter data for the two zoo-ons from Ru80 was that they appeared to have fine structure in their time histories, seen in Figures 3c and 3d. The latter includes a "saw-tooth" like pattern on the more sensitive detector, between about 1 and 100 ms and with an amplitude which is a significant fraction of the main signal amplitude. Interestingly no such structure is evident in either the Alert 747 recordings, or the few other airburst bhangmeter readings that can be found in unclassified (or declassified) literature. They are instead relatively smooth. Such potential fine structure in bhangmeter pulses was one of the issues considered to impose constraints on the properties of a body which could reproduce the observation. Sappenfield, Sowle, McCartor, Possible Origins of Event 747 Optical Data, op. cit.
29. Ibid.
30. Sappenfield, Sowle, McCartor, Possible Origins of Event 747 Optical Data, op. cit., Figure 11.
31. Ibid.
32. Oetzel and Johnson, Vela Meteoroid Evaluation, op. cit.
33. Siegfried Auer, "Instrumentation", in Eberhard Grün, Bo Gustafson, Stan Dermott, and Hugo Fechtig (eds.), *Interplanetary Dust*, (Springer-Verlag, Berlin, 2001), 385–444.
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38. Ibid.
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54. Medina et al., “Reconstruction of a hypervelocity impact event in space,” op. cit. This could feasibly refer to the Vela satellites as they had another optical sensor onboard, a three-axis event locator system designated YBA which was designed to respond to the first maximum of a nuclear detonation. It did not trigger for Alert 747 due to the relatively low signal amplitude, hence the large uncertainty in the inferred event location which covered an area several thousand kilometers in diameter (Mauth, Alert 747, op. cit.).
55. Symbalisty et al., RADFLO Physics and Algorithms, op. cit.; Jones et al., Low-Yield Nuclear Explosion Calculations: The 9/22/79 VELA Signal, op. cit.; Horak, Vela Event Alert 747, op. cit.; Sappenfield et al., “Possible Origins of Event 747 Optical Data,” op. cit.
56. Barasch, “Light flash produced by an atmospheric nuclear explosion,” op. cit.
57. The picture is incomplete, however, since the time of minimum was not measured.
58. Symbalisty et al., RADFLO Physics and Algorithms, op. cit.
59. The calibration is based on Figure 11 in OJ80, converted to Watts, and multiplied by $4\pi R^2$, where R is the Earth-Vela distance. Alert 747 time histories have been taken from a 26 November 1979 draft Sandia/Los Alamos document entitled “22 September 1979 Event” available at digitalarchive.wilsoncenter.org/document/119216.
60. Taken from Figure 8 in Symbalisty et al., RADFLO Physics and Algorithms, op. cit.
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62. Eugene M. D. Symbalisty, Some NUDET Effects due to Water Containment, LA-12775-MS, Los Alamos National Laboratory, 1994.
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