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THE ORION NEBULA: AN ELEPHANT FOR THE BLIND

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RESUMEN

La Nebulosa de Orión es un ejemplo de cómo los científicos, con todas sus fallas humanas realizan investigación. Este artículo describe nuestra comprensión actual de esta famosa nebulosa y demuestra como las intuiciones y los prejuicios han jugado un papel importante en desarrollar la imágen moderna del objeto.

ABSTRACT

The Orion Nebula is a good case study in how science is done by all too human scientists. This article describes our current understanding of this famous nebula and demonstrates how intuitions and biases have played an important role in developing the modern picture of the object.

Key Words: **ISM: H II REGIONS — ISM: INDIVIDUAL: ORION NEBULA — ISM: JETS AND OUTFLOWS — STARS: PRE-MAIN-SEQUENCE**

1. INTRODUCTION

As one of the most beautiful objects in our part of the Milky Way Galaxy and the closest example of star formation that includes hot stars, the Orion Nebula has garnered the attention of many investigators and has led to hundreds of research papers. Research on the object serves as applications of the morals of two well known tales and also illuminates how the process of science actually works.

The first tale is that of "The Blind Men and the Elephant" which appears in many cultures. In this tale the blind work independently and with quite different pieces of information, thereby drawing very different conclusions about the nature of the beast. The second tale is that of the quest of the Princes of Serendip, who made many unanticipated discoveries in their search. These discoveries were the result of being open minded and alert to the unexpected. This tale has given rise to the fashionable word "serendipity".

In addition to illustrating the processes underlying these two tales, research on the Orion Nebula also illustrates several other related and very human processes. I dare say that these generally apply to all areas of science. One tends to find the objects of one's search. All data have uncertainties (both random and systematic) and the tendency is to select the data that agrees with the anticipated result. One of the most powerful confirmations of a theory or model is the original observation of a prediction of the theory. Operating within the fog that always seems to be present at the cutting edge of progress, the all too human scientist defends one's own ideas, sometimes too long. Chutzpah seems to be a necessary ingredient in the composition of the modern scientist; but, we often see the ideas of the the most inflexible being considered long after the countering facts are well known. There is also the related concept of turning radius. In aviation this refers to the fact that any one aircraft has a limit to the radius at which it can change direction. If this is exceeded, the airplane comes apart. The faster it is moving, the larger the turning radius, while if it is moving slowly, it can "turn on a dime". Finally, there is the concept of "choke limit", which says that if you try to force things in at too fast a rate, then nothing goes down. All of these processes have been operating in the study of the Orion Nebula in the 20th Century and some of them may be illustrated in this review paper!

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2. DERIVATION OF THE CORRECT PHYSICAL MODEL

It is difficult at the present to appreciate that the basic physics of gaseous nebulae was not understood until the decade of the 1930's even though the objects had then been recorded for 300+ years (starting with the Orion Nebula) and their 20th century photographs were already famous. Knowledge of the photoionization physics came in bits and pieces (O'Dell 2000a), but it was the key paper by Strömgren (1939) that tied together the physics and the observations to give us what we came to call "Strömgren Spheres". The idea that a hot star embedded in gas would form a spherical volume of ionized gas was so appealing that it immediately found multiple applications. This model became the "lens" through which we viewed all of the Galactic Nebulae. We now know that Strömgren's physics was right, but the model inadequately considered the region of hot star formation. At that time one didn't understand the existence and importance of Giant Molecular Clouds (GMC), whose high volume densities trigger star formation and whose large column densities make them quite optically thick to visual light. As a result, it is the embedded H II regions that appear only in their radio continuum emission that most closely resemble Strömgren's model. There is a strong observational effect operating that means that many and perhaps most of the optically bright H II regions are actually on or near the surface of the GMC that gave birth to the photoionizing hot star. Moreover, these regions must be on the near side of the GMC, i.e. the side facing the observer.

Although these restrictions now seem obvious, the Strömgren Sphere (spherical symmetry) was the model of choice into the 1970's. Osterbrock & Flather (1959) used observations of the [O II] 3727 doublet ratio to determine densities of the emitting gas, finding that it decreased with increasing angular distance from the dominant ionizing star θ^1C Ori. Because the surface brightness predicted from a spherical model with the derived densities was much more than that observed in the radio continuum, they introduced another free parameter into the model, invoking a filling factor to resolve the discrepancy. It was analogous to adding epicycles to save the Ptolemaic model of the Solar System, i.e. uncover a discrepancy, add a new parameter. I too used a spherically symmetric model in interpreting the radial dependence of the strength of the scattered light continuum (O'Dell & Hubbard 1965)! Spherically symmetric models for the Orion Nebula came to a halt with a simple paper by someone not ordinarily working in this field. This often happens since such persons are not fettered by too much knowledge, although it has to be admitted that papers by dilettantes are more often limited by that lack of knowledge of the subject.

Ben Zuckerman (1973) demonstrated that the various discrepancies in the observations of the Orion Nebula would be resolved by assuming that the emitting volume was an ionized layer on the surface of the Orion Molecular Cloud (OMC), i.e. a blister of gas with θ^1C Ori lying in the foreground. The proof of the model came from his pointing out that the progression of observed radial velocities of the emitting gas agreed with what was expected. A modern version of these numbers is shown in Table 1. We know that photoionization stratification is primarily determined by the UV opacity of H, He^0, and He^+. Zones of different ionization will produce different emission lines. Zuckerman then drew on the fact that a photoionized gas on the surface of a vastly more massive GMC would be accelerated away from the GMC, with the material farthest from the GMC having the greatest relative velocity and lowest density. Since the gas must be on the facing side of the GMC (or it would suffer high visual extinction), then the further gas would be more blueshifted and that gas would be of higher ionization due to being closer to θ^1C Ori. At a stroke the need for a filling factor was eliminated and this model quickly gained acceptance. Although not widely appreciated, this model had been proposed (in German) in 1962 by Karl Wurm (1961) who argued from a comparison of the emission line and absorption line velocities near the brightest Orion Nebula Cluster (ONC) stars. This position was strongly refuted by Münch & Wilson (1962) and the blister model lay dormant until being revived by Zuckerman, who presented more definitive proof. Nearly two decades later, Gary Ferland (Baldwin et al. 1991) pointed out that the surface brightness in an emission line like Hα should be directly proportion to the incident flux of ionizing photons, thus explaining the rapid decrease in surface brightness away from the substellar region behind θ^1C Ori. His model was of a flat slab and disregarded several features in the geometry of incoming and emitting radiation, features corrected in the detailed calculations of Wen & O'Dell (1995) who used a detailed application of Ferland's mechanism to determine that the surface of the nebula was actually an irregular concave blister. The cavity around θ^1C Ori is formed by photoevaporation of gas from the OMC, with the irregularities being caused by the photoevaporation proceeding more slowly where the ambient OMC density is higher.

We now know that the central cavity, where θ^1C Ori and the other (ONC) stars are located has a foreground

TABLE 1

THE IONIZATION FRONT BEHIND θ^1C Ori

Zone	Key ion	Markers	$V_\odot$ (km s^{-1})	Density (cm^{-3})	Depth (pc)
PDR	H^0	CO, C II	28	10^5	?
IF	H^+	[O I], [S II]	25.5	$\geq$6000	10^{-4}
Low ionization	He^0	[O II], [N II]	18.8$\pm$1.5	7000	2×10^{-3}
Medium ionization	He^+	[O III], H II, He I, [Cl III]	17.9$\pm$1.3	4000	0.06

Velocities are from Goudis (1982), O'Dell & Wen (1992) and Hu (1996). Densities are from Tielens & Hollenbach (1985), Escalante et al. (1991), Pogge, Owen, & Atwood (1992), Jones (1992) and Walter (1993). IF and low ionization depths are from O'Dell (1994) and O'Dell & Wen (1994).

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veil of interstellar gas, in addition to the background photoionized blister. This foreground veil was obvious even in the first drawings of the nebula as this is what causes the Dark Bay to the east of the Trapezium stars. The veil is also seen in H I 21 cm absorption against the nebular radio continuum and detailed studies show an excellent correlation of the optical extinction (derived from the Balmer decrement) and the column density of H I (O'Dell, Walter & Dufour 1992). We now know that a significant portion of the large scale fluctuations in brightness of the nebula are caused by variations in the column density of this foreground veil (O'Dell & Yusef-Zadeh 2000), which has a characteristic visual optical depth of about 1.5. This lid has a well defined velocity and ionization structure (O'Dell et al. 1993) and possesses a magnetic field of about 200 μG (Troland, Heiles & Goss 1989).

3. THE SCATTERED LIGHT CONTINUUM

It has been established for half a century that the continuum radiation of Galactic Nebulae (including the Orion Nebula) exceeds the expectations of a purely atomic gas (Shain & Gazé 1951). In the case of the Orion Nebula we know that the continuum exceeds that expected from atomic processes (primarily free–bound, free–free, and two–photon emission) by about a factor of five (O'Dell & Hubbard 1965; Baldwin et al. 1991). Given that the ONC stars are dominated by the emission by the Trapezium and this grouping lies in front of the OMC, it is not surprising that the scattered light continuum, which dominates the observed continuum, is particularly strong. In effect, the nebula is a reflection nebula in addition to its emission line properties. The reality of this intrepretation is strengthened by the observations of stellar absorption lines and polarization in the continuum. Dust particles mixed in with the gas will scatter light. Since these are probably well mixed, most of the dust particles in the ionized zone lie beyond the Trapezium and near the main ionization front (MIF) on the surface of the OMC. Moreover, theoretically one expects to find a jump in density in the shock compressed region (the Photon Dominated Region or PDR) just beyond the MIF. If the dust to gas ratio is about that in the general interstellar medium, as indicated for the lid material (O'Dell, Walter & Dufour 1992), then the optical depth within the emitting layer should be about 0.8 in the visual (O'Dell & Yusef-Zadeh 2000). This means that much of the radiation from the stars and the nebular emission should pass beyond the MIF and will be scattered and absorbed in the dense PDR. We probably see the scattered emission line radiation in the redshifted broad component seen at about the 20% level in [O III] emission (O'Dell 1994, O'Dell, Walter & Dufour 1992). The reason it is visible is that the scattering layer is effectively moving away from emitting layer, so that the scattered light is redshifted by twice the relative velocity. This interpretation is expanded upon most thoroughly in a theoretical and interpretive paper of Henney (1998). The scattered light component is impossible to see in Balmer emission because the large thermal width of those lines mask the redshifted component. In the case of the other massive ions (thereby having less thermal width) the relative velocity with respect to the scattering layer is less and the scattered lines fall at about the same velocity as the emitted lines.

This process may have repercussions, since the exact fraction of radiation scattered will depend upon the wavelength and the separation of the emitting and scattering layers. This means that the mechanism can be introducing a variation in the uncertainty of the relative intensities of emission lines, since some lines may have a larger undetected component of scattered light than others. No matter what the accuracy of the extinction corrections and the inherent accuracy of the spectrophotometry, this "scattered light noise" will still be present and should be considered when trying to interpret low spectral resolution emission line ratios.

4. FINESCALE DYNAMICS OF THE ORION NEBULA

Although there are systematic changes in the local radial velocity of the gas (Wilson et al. 1997) these variations probably reflect location variations in the orientation of the MIF. There is some evidence that there is a global flow to the southwest, which is a direction that is not covered by the foreground veil.

The finescale structure of radial velocities has been addressed multiple times, the first distinctive investigation being that of the [O III] 5007 Å line by Wilson et al. (1959), who mapped radial velocities across the entire bright portion of the nebula. This investigation was repeated by Castañeda (1988) using comparable velocity resolution (about 6 km s^{-1}) but CCD's, which allowed detailed analysis of the line profiles. His study was followed by a series of Rice University PhD theses ([O II], Jones 1992; [O I] O'Dell & Wen 1992; [S III] Wen & O'Dell 1993; and less complete sampling in [N II] and [S II] Hu 1996). The analysis of these data have followed the lead of Münch (1958) who interpreted the original [O III] observations. He demonstrated that a useful method of analyzing the fine scale fluctuations in radial velocity ($V(\phi)$) about the average value is through the Structure Function ($B(\phi)$), calculated as $B(\phi) = <\mid V(\phi') - V(\phi'') \mid^2>$, where ϕ refers to the angular separation of two samples located at positions ϕ' and ϕ'' and $B(\phi)$ is calculated for all combinations of velocity samples.

Von Hörner (1951) had calculated the behavior of the Structure Function for a turbulent gas distributed in a thin layer. He showed that in the case where the turbulent velocity varies as a power law of index n, that $B(\phi)$ increases with a slope of n for values of ϕ much larger than the emitting layer thickness, and as n+1 for separations small compared with that thickness. If the turbulence is driven by power sources of several sizes, the observed indices will be less, although the transition from one regime to the other occurs at the same size. The several recent studies agree with Münch's conclusion that a break occurs at a separation of about 20", which corresponds to a thickness of about 0.04 pc, i.e. within a factor of two of the derived equivalent thickness of the emitting layer (Table 1). This apparent agreement is perplexing since the emitting layer in [O II] should be much thinner than that of [O III], so that the transition should occur at quite different scales. In the case of [O I] emission there is an essentially constant slope of $B(\phi)$, which is to be expected since all sample separations are large compared with the emitting layer thickness in that atom. In addition, in the case of [O I] the power law inferred is quite close to the value of 2/3's expected for Kolmogorov turbulence. Therefore, we see that there is some agreement between observations and the expectations of turbulence occurring in a thin slab, but there are numerous remaining disagreements.

5. THEORETICAL MODELS OF THE ORION NEBULA

By theoretical models I mean models generated in great analytical detail under a given set of assumptions, which contrasts with models derived directly from the observations, as discussed in § 2. There are two such models, published almost simultaneously and both trying to approximate the basic blister model. In the model of Rubin et al. (1991a,b) the MIF was prescribed to be a plane in front of which the density of material decreased exponentially. Although successful in matching the relative emission line ratios near the source of ionization, the agreement further away was not satisfactory. In contrast, Baldwin et al. (1991) used the more complete CLOUDY photoionization code to treat a flat slab model. The density distribution was not prescribed, rather, it was calculated from equating the radiation pressure to the outward force due to a pressure gradient. In addition, Ferland's mechanism (surface brightness measured from the photoionizing star being directly proportional to the local flux of ionizing photons) was introduced and the resulting line ratios were in good general agreement with the optical observations. Neither of these models is really satisfactory, for they do not take into consideration the concave nature of the MIF, nor do they simultaneously solve both the hydrodynamic and photoionization equations. The exponential density distribution assumed by Rubin et al. is actually quite realistic for a freely expanding gas, so that helps their model in being more realistic, even though the assumption is ad hoc. The Baldwin et al. model calculates the density distribution as part of the solution under the assumption that an equilibrium against radiation pressure will occur, although Henney

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& Arthur (1997) argue that the density gradient force will always be much less (about 1/30) than the gas pressure, so that one does have to solve the detailed hydrodynamic plus photoionization model. In analogy to the observers who make the best observations they can, even if they know that this may not be covering all of the important diagnostic information, the theoreticians are calculating the most realistic tractable models, even though they know them to be not fully realistic. One proceeds in steps of increasing sophistication.

6. EXTINCTION AND ABSORPTION IN THE DIRECTION OF THE ORION NEBULA

There are two distinct mechanisms operating here. Study of the absorption lines imposed on the smooth continuum of the hottest ONC stars gives measures of the column density of particular atoms and ions along the very narrow but well defined lines of sight to those stars. The interstellar grains along lines of sight to the nebula will scatter and absorb nebular radiation. The existence of the foreground veil of material was first found through seeing 21 cm H I lines in absorption against the nebular radio continuum. The fact (O'Dell et al. 1992) that this is correlated with the reddening derived from the Balmer decrement argues that most of that extinction originates within the lid. Velocity coincidences argue that the observed interstellar lines of Na I and Ca II are formed in this same foreground lid (O'Dell et al. 1993). The strength and velocity of the He I 3889 Å absorption line is more difficult to interpret (Münch & Wilson 1962; O'Dell et al. 1993). It most certainly is formed in the ionized zone surrounding the Trapezium stars, since the lower energy state for the transition is the lowest triplet state 2^3S, which is populated by recombinations of He^+. The large relative velocities of this line with respect to the Trapezium stars argues that there are one or more expanding shells of material within the low density part of the nebula. This could be produced through the stellar wind of θ^1C Ori, or from the numerous shocks driven by collimated outflows from low mass stars (as discussed in the next section).

Now that good angular resolution (about 1.6") radio continuum images from the VLA are available, comparison of this emission with the Hα surface brightness has allowed a fine grid determination of the extinction across the face of the nebula (O'Dell & Yusef-Zadeh 2000). This has revealed the presence of stellar and sub-stellar mass knots in the Dark Bay region. It has also shown that the extinction corrected appearance of the nebula is still quite splotchy. A detailed study of the ionization variations shows that the MIF must be highly irregular. We had known previously that the Bright Bar was produced when the MIF was tipped up almost along the line of site. We now see that there are many similar features, i.e. linear features caused by escarpments in the MIF. These results are good examples of utilizing information resulting from feeling different parts of the elephant (i.e. using data from very different observing techniques).

7. STAR FORMATION AND OUTFLOWS

The advent of Hubble Space Telescope (HST) imaging of the Orion Nebula has fundamentally expanded how we view the process of star and planet formation in young clusters containing massive stars. We now know that most low mass young stars are associated with circumstellar disks and are the sources of both collimated and general outflows. Since the images that initially revealed the circumstellar disks were made to study the structure of the nebula, this can be counted as a serendipitous discovery.

The historical reality is not so clearly black and white, which is often the case. There were several regions of known high velocity outflow that had already been identified. The pair of shocks called HH 203-204 near θ^2A Ori were identified quite early (Münch & Wilson 1962) since they fall just beyond the Bright Bar, where the nebular surface brightness has dropped significantly and their contrast with that background is quite high. The objects HH 201 and HH 205-210 are all quite low ionization and stand out in contrast with the nebula (Axon & Taylor 1984) and are now known to be the tips of fingers of shocked material driven by a source embedded within the OMC near the source IRc-2 (O'Dell et al. 1997a). HH 202 has several features of high surface brightness and was also seen from ground images (Cantó et al. 1980).

Quasi-stellar ionized sources of high ionization had been detected by Laques & Vidal (1979) and all of these were included in a very high resolution VLA survey by Churchwell et al. (1987). The earliest interpretations were wrong in calling them Partially Ionized Globules (meaning that these were possibly pre-stellar gas clouds); but, Churchwell et al. identified the correct model as one of several possible interpretations of their observations. The HST images showed their natures clearly. In fact their nature is so obvious that in retrospect we know that we should have been looking for just these objects. Moreover, the fact that the author thought he was making a

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truly original discovery is a measure of the failure to really understand results made in other wavelengths, this being yet another example of the blind men feeling different parts of the elephant and not understanding what the other observers have found. In a series of papers (O'Dell, Wen & Hu 1993; O'Dell & Wen 1994; O'Dell & Wong 1996) it was shown that most low mass stars in the ONC have circumstellar clouds which are partially ionized by θ^1C Ori and θ^2A Ori. These are designated as "proplyds", which mean circumstellar clouds around low mass stars that are rendered visible because of being in or near an H II region. Earlier infrared observations of other regions of young low mass stars had already established that circumstellar disks should be common. What sets the proplyds apart is the special location, which affects their visibility and possibly their lifetimes.

Most of the proplyds appear as bright cusps. These are the ionization boundaries formed on the side facing the dominant ionizing star. Within the cusps and closer to the associated low mass star is a neutral molecular disk of material, the dust component of which makes them visible as dark features. In the case of proplyds located within the foreground neutral veil of material the Lyman continuum (LyC) photons are filtered out and the objects are neutral throughout, but are seen in silhouette against the bright nebular background. The standard model that has evolved is that the inner molecular neutral disk is heated by low energy UV photons, producing an expanding wind of gas within which the local ionization front is then formed.

The much higher spatial resolution of the HST has also revealed a myriad of high ionization shocks that are driven by outflows from the proplyds. Their spatial motions are sufficiently high that their tangential motions have already been measured (Bally, O'Dell & McCaughrean 2000), which allows determination of their origin. Most of these are shocks formed when collimated outflows interact with ambient nebular gas, which is already ionized. HH 202 and HH 203+204 are examples of shocks formed as the collimated gas strikes the neutral foreground veil material. A few other shocks form from the interaction of a general wind of material off the young low mass star with ambient nebular material. In 20 objects we see microjets coming out from the stars at velocities of up to several hundred km s^{-1}. All of this fits nicely into the general paradigm for star formation, but in this case we are dealing with the type of cluster which is thought to be most characteristic of star formation.

The study of the jets and shocks gives yet another example of the need to integrate results obtained by different methods. The object now designated as HH 529 was not recognized until low spatial resolution Fabry–Pérot velocity sampled images were made (O'Dell et al. 1997b). Using these as a guide, one could go back to the complex structures seen in the HST images and discern the true high velocity features.

The Churchwell et al. paper had correctly shown that if the proplyds were photoionized and had masses similar to other circumstellar disks they should survive photoevaporation only about 10^5 years. As the reality of the model sank in, theoreticians (Henney & Arthur 1998; Johnstone et al. 1998) quickly refined the calculations for photoevaporation rates and used new and small values for the masses (Lada et al. 1996; Bally et al. 1998), reducing the predicted survival age even further, to the point that they were much shorter than the age of the ONC (3×10^5-10^6 years), i.e. the objects were ephemeral and probably not a source of planets. In an illustration of defending ones ideas and discoveries, the author attempted first to invoke continuum radiation pressure as a means of preventing photoevaporation (O'Dell & Wen 1994) and then radiation pressure (O'Dell 1998) from scattered Lyα photons, both of which quantitatively can be shown to be insufficient to prevent photoevaporation. Henney & O'Dell (1999) addressed the problem more directly by obtaining Keck high resolution spectra of four proplyds. These spectra show that photoevaporation does seem to be occurring at the theoretically predicted rate and can produce lifetimes as short as about 10^4 years. The resolution of this conundrum (that the lifetimes are very short compared with what must be their illumination times) is still not clear. It has been suggested that the objects are in quite elliptical orbits (there is little direct support for this) or that θ^1C Ori has actually been cloaked until very recently. In any event, there is no evidence for depletion of the gaseous envelopes even in the proplyds closest to θ^1C Ori, so the mystery remains.

8. SHADOWS OF THE PROPLYDS

Processes first articulated to explain specific phenomenon often find unexpected applications. This is the case with the theory of the ionization shadow that would exist behind a knot optically thick to the LyC, as first proposed by Van Blerkom & Arny (1972) to explain radial structures in planetary nebulae. This theory was more recently expanded by Cantó et al. (1998) in an effort to explain the radial filaments trailing behind the cometary knots in the Helix Nebula (O'Dell & Burkert 1997). The basic process is that a small feature

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embedded within a photoionized gas will shield a tapered column from direct illumination by stellar LyC photons with any photoionization within that column being due to scattered LyC photons. In a low density gas this column will be fully ionized, although it will have a deficit of the higher ionization states of heavy ions. When the density is high, there can be a neutral column down the central part of the shadowed region, with corresponding ionization stratification.

An examination of [N II]/Hα and [O III]/Hα HST images shows a number of highly linear structures of up to 4x10^{17} cm length, demonstrating relatively enhanced [N II] and diminished [O III]. A closer inspection shows that each of these is exactly aligned with a proplyd and that a projection of the line passes through θ^1C Ori. When the search is reversed, it is found that essentially all of the proplyds close to θ^1C Ori show detectable linear shadows. The results of such a search and comparison with the Cantó et al. formulation of the theory has been made (O'Dell 2000b) and excellent agreement is found. In those shadows with neutral cores one can see the [O I] and [S II] emission that traces an ionization front. The shadow usually does not extend back to the proplyd itself and this is to be expected, because there must be dense material being shadowed in order to produce a shadow that is visible. Most of the material in the Orion Nebula is close to the MIF, while the proplyds and other young stars lie in the low density zone well in front of the OMC. This process can be used to help delineate the three dimensional placement of θ^1C Ori and the individual proplyds. The same paper shows how the process is successful in explaining the HST images of the Helix Nebula cometary knots. It is a good example of how a basic physical process can often find application quite far afield from its initial application.

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