Internal structure of a cold dark molecular cloud inferred from the extinction of background starlight

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Stars and planets form within dark molecular clouds, but little is understood about the internal structure of these clouds, and consequently about the initial conditions that give rise to star and planet formation. The clouds are primarily composed of molecular hydrogen, which is virtually inaccessible to direct observation. But the clouds also contain dust, which is well mixed with the gas and which has well understood effects on the transmission of light. Here we use sensitive near-infrared measurements of the light from background stars as it is absorbed and scattered by trace amounts of dust to probe the internal structure of the dark cloud Barnard 68 with unprecedented detail. We find the cloud's density structure to be very well described by the equations for a pressure-confined, self-gravitating isothermal sphere that is critically stable according to the Bonnor–Ebert criteria[1,2]. As a result we can precisely specify the physical conditions inside a dark cloud on the verge of collapse to form a star.

Molecular clouds are primarily composed of molecular hydrogen mixed with trace impurities including interstellar dust grains and rare organic and inorganic molecules. Because of its symmetric structure the hydrogen molecule possesses no dipole moment and cannot produce a readily detectable signal under the conditions that characterize cold, dark clouds. The traditional methods used to derive the basic physical properties of such molecular clouds therefore make use of observations of trace H_2 surrogates, namely those rare molecules with sufficient dipole moments to be easily detected by radio spectroscopic techniques, and interstellar dust, whose thermal emission can be detected by radio continuum techniques. However, the interpretation of results derived from these methods is not always straightforward[3,4]. Several poorly constrained effects inherent in these techniques (such as deviations from local thermodynamic equilibrium, opacity variations, chemical evolution, small-scale structure, depletion of molecules, unknown emissivity properties of the dust, unknown dust temperature) make the construction of an unambiguous picture of the physical structure of these objects a very difficult task. The deployment of sensitive, large-format infrared array cameras on large telescopes, however, has altered this situation by enabling the direct measurement of the dust extinction (that is, the overall diminution of starlight due to the combined effects of absorption and scattering by dust) toward thousands of individual background stars observed through a molecular cloud. Such measurements are free from the complications that plague molecular-line or dust emission data and enable detailed maps of cloud structure to be constructed[5–7].

Recently we performed very sensitive near-infrared imaging observations to map the structure of a type of dark cloud known as a Bok globule[8,9], one of the least complicated configurations of molecular gas that is known to form stars. The target cloud for our study, Barnard 68, is itself one of the finest examples of a Bok globule, and was selected because it is a nearby, relatively isolated and morphologically simple molecular cloud with distinct boundaries, a known distance (125 pc; ref. 10), and temperature (16 K; ref. 11). Barnard 68 appears to be part of a string of dense clouds (Barnard 68, 69 and 70) located within a well known superbubble of hot gas, Loop I, created by the combined action of stellar winds and supernova explosions[12,13] from extinct massive stars which were once part of the Scorpio–Centaurus OB association. This cloud lies in the direction of the centre of the Galaxy but above the Galactic

Figure 1 Visible and near-infrared images of Barnard 68. Top, deep B,V,I band (0.44 μm, 0.55 μm, 0.90 μm) image (~7′ × 7′) of the dark molecular cloud Barnard 68 taken with ESO's Very Large Telescope (VLT) located in the Chilean Andes. The cloud is seen in projection against the Galactic bulge. At these optical wavelengths the cloud is completely opaque owing to extinction of background starlight caused by small interstellar dust particles that permeate the cloud. The complete absence of foreground stars projected onto the cloud is a result of the proximity of the cloud to the Solar System (125 pc). The outer radius of the cloud is comparable to the inner size of the Oort cloud of comets that surround the Sun (~10^4 AU). The mass of the cloud is about twice that of the Sun. Bottom, deep B,I,K band image of the cloud constructed by combining an infrared K band (2.2 μm wavelength) image with the B and I images. The K band image was obtained with ESO's New Technology Telescope (NTT) in the Chilean Andes. At near-infrared wavelengths the cloud becomes transparent and the stars located behind the cloud clearly appear in the image. Because these stars are observed only in the longest of the three wavelength bands, they appear very red in this three-colour image. These are the stars that provide measurements of dust extinction directly through the cloud.

plane where it is projected against the rich star field of the Galactic bulge. This makes Barnard 68 an ideal candidate for an infrared extinction study for the following four reasons. First, the background bulge stars are primarily late-type (giant) stars whose intrinsic infrared colours span a narrow range and can be accurately determined from observations of nearby control fields. Second, the background star field is sufficiently rich to permit a detailed sampling of the extinction across the entire extent of the cloud. Third, the cloud is sufficiently nearby that foreground star contamination is negligible. Fourth, Barnard 68 does not appear to harbour any star-formation activity[14], making it more likely that the physical conditions that characterize it reflect the initial conditions for star formation.

We used the SOFI[15] near-infrared camera on the European Southern Observatory's (ESO) New Technology Telescope (NTT) to obtain deep-infrared J band (1.25 μm), H band (1.65 μm) and K band (2.16 μm) images of the cloud over two nights in March 1999. Complementary optical data were obtained with ESO's Very Large Telescope (VLT) on Cerro Paranal, fitted with the FORS1 (ref. 16) charge-coupled device (CCD) camera, during one night of March 1999. The results of the optical and near-infrared imaging are displayed in Fig. 1 top and bottom. At optical wavelengths obscuring dust within the cloud renders it opaque and completely void of stars (Fig. 1 top). However, owing to the wavelength dependence of dust extinction (that is, opacity), the cloud is essentially transparent at infrared wavelengths, enabling otherwise invisible stars behind the cloud to be imaged (Fig. 1 bottom). We detected 3,708 stars simultaneously in the deep H and K band images out of which ~1,000 stars, lying behind the cloud, are not visible at optical wavelengths. Because dust opacity decreases sharply with wavelength, the colours of stars that are detected through a dust screen appear reddened in comparison to their intrinsic colours (for example, Fig. 1 bottom). Because the amount of reddening is directly proportional to the total extinction, we can determine the line-of-sight extinction to each star using a standard reddening law for interstellar dust and knowledge of the star's intrinsic $(H - K)$ colour[5,6]. We determined very accurate individual line-of-sight extinction measurements for all the 3,708 stars that we detected by adopting: (1) the average colour of bulge stars observed in a nearby unreddened control field as the intrinsic colour for all stars in our target field; and (2) a standard interstellar reddening law[17]. In this manner we have accurately sampled the dust extinction and column density distribution through the Barnard 68 cloud at more than 1,000 positions with extraordinary (pencil beam) angular resolution. Although the individual measurements are characterized by high angular resolution, our mapping of the dust column density in the cloud is highly undersampled. Consequently, we smoothed these data to construct an azimuthally averaged radial extinction (dust column density) profile of the cloud and present the result in Fig. 2. To our knowledge, this is the most finely sampled and highest signal-to-noise radial column density profile ever obtained for a dense molecular cloud. The extinction profile in Fig. 2 is the two-dimensional projection of the cloud volume density profile function, $\rho(r)$ where r is the radial distance from the centre of the cloud, and therefore provides an excellent map of the internal structure of this dense dark cloud.

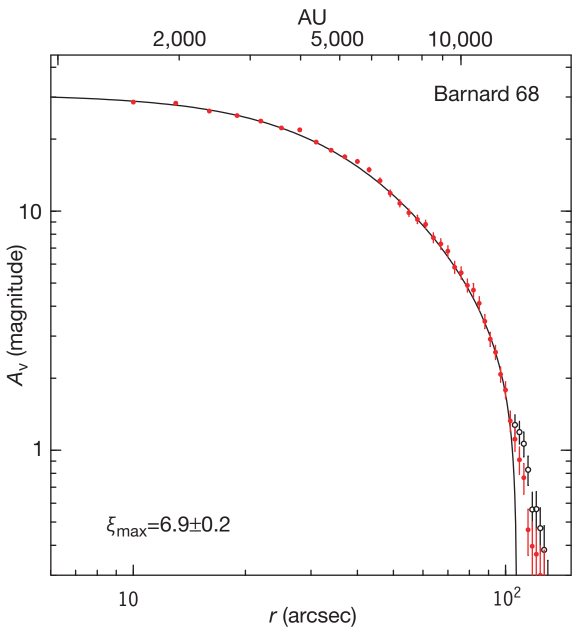

Figure 2 Azimuthally averaged radial dust column density profile of Barnard 68. By convention the dust column density is expressed in terms of magnitudes of visual extinction, A_V. The red circles show the data points for the averaged profile of a subsample of the data that do not include the cloud's southeast prominence, seen in Fig. 1. The open circles include this prominence. The error bars were computed as the r.m.s. dispersion of the extinction measurements in each averaging annulus and are smaller than the data points for the central regions of the cloud. The solid line represents the best fit of a theoretical Bonnor–Ebert sphere to the data. The close match of the data with theory indicates that the internal structure of the cloud is well characterized by the equations for a self-gravitating, pressure-confined, isothermal sphere and thus Barnard 68 seems to be a distinct dynamical unit near a state of hydrostatic equilibrium, with gravity balanced by thermal pressure.

As early as 1948 Bok[18] pointed out that roughly spherical homogeneous-looking clouds, such as Barnard 68, resemble single dynamical units much like the polytropic models[19,20] used to describe stellar structure. Can Barnard 68 be described as a self-gravitating, polytropic sphere of molecular gas? To investigate the physical structure of the cloud we begin with the assumptions of an isothermal equation of state and spherical symmetry. The fluid equation that describes a self-gravitating, isothermal sphere in hydrostatic equilibrium is the following well known variant of the Lane–Emden equation[21].

$$\frac{1}{\xi^2}\frac{\mathrm{d}}{\mathrm{d}\xi}\left(\xi^2\frac{\mathrm{d}\psi}{\mathrm{d}\xi}\right) = e^{-\psi} \tag{1}$$

where $\xi = (r/a)\sqrt{4\pi G\rho_c}$ is the non-dimensional radial parameter, a is the isothermal sound speed ($a = \sqrt{kT/m}$), ρ_c is the volume density at the origin, and $\psi(\xi) = -\ln(\rho/\rho_c)$. Equation (1) is Poisson's equation in dimensionless form for the gravitational potential, ψ, when the volume density for an isothermal gas is given by the barometric formula to be proportional to the $e^{-\psi}$, and it can be solved by numerical integration subject to the usual boundary conditions:

$$\psi(0) = 0 \text{ (that is, } \rho = \rho_c \text{ at } r = 0)$$

$$\text{and } \frac{\mathrm{d}\psi(0)}{\mathrm{d}\xi} = 0 \left(\text{that is, } \frac{\mathrm{d}\rho}{\mathrm{d}r} = 0 \text{ at } r = 0\right)$$

For an isothermal sphere bounded by a fixed external pressure there is a family of solutions characterized by a single parameter:

$$\xi_{max} = \frac{R}{a}\sqrt{4\pi G\rho_c} \tag{2}$$

Here ξ_{max} is the value of ξ at the outer boundary, R (refs 1, 2). Each of these solutions corresponds to a unique cloud mass density profile. For $\xi_{max} > 6.5$ such a gaseous configuration would be unstable to gravitational collapse[2]. The high quality of our extinction data permits a detailed comparison with the Bonnor–Ebert predictions and we find that there is a particular solution, $\xi_{max} = 6.9\,(\pm 0.2)$, that fits the data extraordinarily well as seen in Fig. 2. This solution corresponds to a centre-to-edge density contrast of $\rho_c/\rho_R = 16.5$, which is slightly in excess of the critical contrast (14.0) predicted by the Bonnor–Ebert theory. For the known distance (125 pc), and temperature (16 K), Barnard 68 has a physical radius of 12,500 AU, a mass of 2.1 solar masses, and a pressure at its boundary of $P = 2.5 \times 10^{-12}$ Pa. This surface pressure is an order of magnitude higher than that of the general interstellar medium[22] but it is in rough agreement with the pressure inferred for the Loop I superbubble from X-ray observations with the ROSAT satellite[13]. The close correspondence of the observed extinction profile with that predicted for a Bonnor–Ebert sphere strongly suggests that Barnard 68 is indeed an isothermal, pressure-confined and self-gravitating cloud. It is also likely to be in a state near hydrostatic equilibrium with thermal pressure primarily supporting the cloud against gravitational contraction.

For Barnard 68, ξ_{max} is very near and slightly in excess of the critical radial parameter and the cloud may be only marginally stable and on the verge of collapse. However, in the likely case that the cloud contains a static magnetic field[23–25], the additional internal magnetic pressure can act to stabilize it at a density contrast slightly higher than that predicted by the Bonnor–Ebert theory. Nevertheless, inevitable physical processes, such as cloud cooling, the natural reduction of internal magnetic flux by ambipolar diffusion[26,27], as well as any increase in external pressure, will readily destabilize the Barnard 68 cloud and result in the formation of a low-mass star, similar to the Sun.

Finally, we suggest that Barnard 68, and its neighbouring globules B69, B70 and B72 may be the precursor of an isolated and sparsely populated association of young low-mass stars similar to the recently identified TW Hydra[28] association. The TW Hydra association is a stellar group near the solar system consisting of a handful of young low-mass, Sun-like stars. The existence of such a young stellar group presents an interesting problem to astronomers because its origin is difficult to explain given its youth and relatively large distance from known sites of star formation. Bok globules such as those in the Barnard 68 group are thought to be remnant dense cores produced as a result of the interaction of massive O stars and molecular clouds[29]. Over their short lifetimes such massive stars, through ionization, stellar winds and ultimately supernova explosions, very effectively disrupt the molecular clouds from which they formed. In the process large shells of expanding gas are created. When surrounding clouds are disrupted by the passage of these shells, a few of their most resilient dense cores will be left behind, embedded within the shell's hot interior. Remnant cores with just the right mass can establish pressure equilibrium with the hot gas within the shell and survive to become Bok globules. Eventually, as a result of the processes described above, these clouds will evolve to form low-mass, Sun-like stars which are relatively isolated and far from the original birthplace of the O stars. Up to 35% of all Bok globules contain newly formed stars[30] and thus it is likely that our observations of the starless Barnard 68 cloud provide the first detailed description of the initial conditions which exist before the collapse of dark globules and the formation of isolated, low-mass stars. □

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Quantum metallicity in a two-dimensional insulator

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One of the most far-reaching problems in condensed-matter physics is to understand how interactions between electrons, and the resulting correlations, affect the electronic properties of disordered two-dimensional systems. Extensive experimental[1–6] and theoretical[7–11] studies have shown that interaction effects are enhanced by disorder, and that this generally results in a depletion of the density of electronic states. In the limit of strong disorder, this depletion takes the form of a complete gap[12,13] in the density of states. It is known that this 'Coulomb gap' can turn a pure metal film that is highly disordered into a poorly conducting insulator[14], but the properties of these insulators are not well understood. Here we investigate the electronic properties of disordered beryllium films, with the aim of disentangling the effects of the Coulomb gap and the underlying disorder. We show that the gap is suppressed by a magnetic field and that this drives