Substantia
An International Journal of the History of Chemistry

Firenze University Press
www.fupress.com/substantia

OPEN ACCESS

Citation: Ninham B. W., Brevik I., Malyi O. I., Boström M. (2023) A Role for Bose-Einstein Condensation in Astrophysics. *Substantia* 7(2): 35-39. doi: 10.36253/Substantia-2091

Received: Mar 21, 2023

Revised: May 23, 2023

Just Accepted Online: Jun 06, 2023

Published: September 21, 2023

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing Interests: The Author(s) declare(s) no conflict of interest.

Research Article

A Role for Bose-Einstein Condensation in Astrophysics

Barry W. Ninham[1], Iver Brevik[2], Oleksandr I. Malyi[3], Mathias Boström[3],*

[1] *Department of Materials Physics, Research School of Physics, Australian National University, Canberra, Australia*
[2] *Department of Energy and Process Engineering, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway*
[3] *Centre of Excellence ENSEMBLE^3 Sp. z o. o., Wolczynska Str. 133, 01-919, Warsaw, Poland*
E-mail addresses: Barry.Ninham@anu.edu.au; iver.h.brevik@gmail.com; oleksandr.malyi@ensemble3.eu; Mathias.Bostrom@ensemble3.eu
*Corresponding author.

Abstract. We revive a 60-year-old idea that might explain a remarkable new observation of a periodic low-frequency radio emission from a source at galactic distances (GLEAM-X J162759.5-523504.3). It derives from the observation that a high-density high-temperature charged boson plasma is a superconducting superfluid with a Meissner effect.

Keywords: Bose-Einstein condensate, Charged Bose gas, astrophysical chemistry.

INTRODUCTION

Sporadic forays over the years have explored the possibility that the physics of Bose-Einstein condensation ought to play some role in Astrophysics, e.g. [1,2]. Many of the particles involved in stellar evolution are bosons, i.e. have zero or integer spin. Bose-Einstein condensation is a fundamental macroscopic manifestation of quantum physics. It would seem remiss of the Creator not to have employed the phenomenon somewhere in building the Universe. Especially is this so since Fermi-Dirac and Classical Statistical Mechanics do figure largely. A suggestion of a role for Bose-Einstein condensation was made 60 years ago when quasars were first observed [1], and forgotten. Later attempts failed because they considered superconductivity and Bose condensation as classical low-temperature phenomena like that which occurs for electrons in metals. But the phenomena are not limited and exist for very high-temperature high-density charged particles [1].

We here revive that 60-year-old idea and suggest it might explain a recent extraordinary observation.

THE PHENOMENON

Hurley-Walker *et al.* [3] recently reported an unusually slow periodic low-frequency radio emission from a source at galactic distances (GLEAM-X J162759.5-523504.3) with a pulse period of 18.18 minutes. One clue to its origin is that high linear polarization has been shown to be characteristic of a source with strongly ordered magnetic fields [4-6]. The observations are unlike emissions characteristic of stars, white dwarfs, white binaries, or exoplanets. Furthermore, the 0.5-light-second upper limit on the object's size and estimated brightness temperature of 10^{16} K led Hurley-Walker *et al.* [3] to propose that a radiation source is a compact object with a rotational origin.

THE IDEA

With that in mind, we give reasons to consider if Bose-Einstein condensation [1] might have something to do the phenomenon:

(i) Stable nuclei in stellar interiors have zero or integer spin. Nuclei of higher and higher atomic numbers built up during the evolution of stars. They are charged bosons.
(ii) A dense charged high-temperature boson plasma becomes nearly perfect as density increases (i.e., the Coulomb collective interactions become so weak that they can be ignored, and we can work with the perfect gas approximation).
(iii) It can undergo Bose-Einstein condensation to a superfluid state.
(iv) A conducting superfluid is a superconductor. A rotating superconducting superfluid has a Meissner effect. That is, it expels the magnetic field generated by rotation.
(v) Such a magnetic field would be trapped in the lower-density surface region. This process continues as the star collapses and its rotation speeds up.
(vi) Massive synchrotron radiation follows that dissipates this increasing build-up of energy.

The assumptions i-vi were originally made 60 years ago to explain the newly discovered quasars. Schafroth [8], Blatt [9], and Butler [10] had shown earlier that an ideal charged Bose gas below the critical point for superfluidity is a superconductor (see also Refs. [7,8-17]). These theories [7-17] call on electron pairing to generate charged bosons that then lead to Bose condensation and superconductivity *at very low temperatures.* Our situation is quite different. The stellar objects involve real boson nuclei of even spin. The high-density, high-temperature plasmas are close to ideal.

We recall the process of nucleosynthesis in stellar interiors [18-21]. The theory explains how nuclear reactions convert lighter elements into heavier ones through the fusion of atomic nuclei. As the star evolves, the fuel elements involve successive steps, with H, He, C, O, Ne, Si, Fe, and U providing increasingly heavier energy sources that drive the stellar evolution to completion [18]. We need to estimate the critical temperatures and core densities for Bose condensation for stars with different fuel elements to check that they can have a Boson core region.

CALCULATIONS

Consider an assembly of ions of even spin, mass *M and charge Ze*, in a background electron gas. Under extreme high-density and high-temperature conditions, the system is expected to behave like a mixture of ideal gases. That can be achieved by ensuring that the average energy of Coulomb interactions between two ions is small compared to their kinetic energy. At densities approaching the critical value for Bose-Einstein condensation of ions, i.e., when their chemical potential approaches zero, the mean energy, per particle of the ideal Bose gas is approximately equal to *kT*. The average distance between the particles is then [1]

$$\mathrm{r} \approx 2\sqrt[3]{3\mathrm{M}/[4\pi\rho]} \approx \lambda = h/(Mv) = h/\sqrt{2\ \mathrm{M\,kT}}, \tag{1}$$

where λ is the de Broglie wave length of an ion of mass *M* and kinetic energy ~*kT* (taken in Eq (1) equal to $\mathrm{Mv}^2/2$). The condition that the actual gas be nearly ideal is [1]

$$\frac{2Z^2e^2}{r} \ll \mathrm{kT}. \tag{2}$$

Hence, taking the requirement Eq. (2) with Eq. (1), the critical expressions for temperatures, density, and particle separation can be estimated to be of the order

$$T_C \sim \frac{8MZ^4e^4}{h^2k} \tag{3}$$

$$\rho_C \sim \frac{384}{\pi}\frac{M^4Z^6e^6}{h^6} \sim \frac{6}{8\pi}\frac{Mk^3}{Z^6e^6}T_C^3, \tag{4}$$

$$\mathrm{r}_C \sim \frac{h^2}{4MZ^2e^2} \sim \frac{2Z^2e^2}{kT_C}. \tag{5}$$

The numerical values are summarized in Table 1. We expect that highly charged nuclei will be "dressed" by an inhomogeneous adsorbed relativistic electron cloud (mesons in another guise): just as for charged micelles or highly charged ions in electrolyte solutions. In that case, "bound" counterions are typically 80-90% of the bare charge. The effective charge is 10-20% of the actual charge. Without recognising such screening, estimated critical parameters for the separation of heavy ions become unphysical and ridiculous. In Table 1, we take two extreme estimates to bound these uncertainties: the unscreened Z and Z=1. To illustrate our point, we present also the critical temperatures with 10% and 20% effective charges in Table 2. For Uranium, from Table 2, the estimated critical temperatures are 10^{14} K<T_c<10^{15} K. These bounds are similar in magnitude to the observed brightness temperature of 10^{16} K discussed by Hurley-Walker *et al.* [3].

Table 1. The critical temperatures and mass densities for different fuel elements in the core of a Boson star are derived from Equations (3)-(5). Since we did not include screening we present two different estimates (a) based on setting Z=1 (columns 2 and 3) and (b) using Z from column 1 (columns 4 and 5). Here $h = 6.626\times10^{-27}$ erg s, $k = 1.381\times10^{-16}$ erg/K, $e = 4.803\times10^{-10}$ esu, and we estimate the mass as $M = A\times1.66\times10^{-24}$ g (Atomic number × proton mass).

Fuel element [A,Z]	T_C (Z=1) [K]	ρ_C (Z=1) [g/cm^3]	T_C (Z) [K]	ρ_C (Z) [g/cm^3]
He [4,2]	4.7×10^8	3.5×10^{10}	8×10^9	2×10^{12}
C [12,6]	1.4×10^9	2.9×10^{12}	2×10^{12}	1×10^{17}
O [16,8]	1.8×10^9	9.0×10^{12}	8×10^{12}	2×10^{18}
Ne [20,10]	2.3×10^9	2.2×10^{13}	2×10^{13}	2×10^{19}
Si [28,14]	3.2×10^9	8.5×10^{13}	1×10^{14}	6×10^{20}
Fe [56,26]	6.6×10^9	1.3×10^{15}	3×10^{15}	4×10^{23}
U [238,92]	2.8×10^{10}	4.4×10^{17}	2×10^{18}	3×10^{29}

Table 2. The critical temperatures for different fuel elements in the core of a Boson star are derived from Equations (3)-(5). Estimates (a) based on setting $Z\rightarrow Z\times0.1$ (column 2) and $Z\rightarrow Z\times0.2$ (column 3). Constants used are same as in Table 1.

Fuel element [A,Z]	T_C (Z→Z×0.1) [K]	T_C (Z→Z×0.2) [K]
He [4,2]	8×10^5	1×10^7
C [12,6]	2×10^8	3×10^9
O [16,8]	8×10^8	1×10^{10}
Ne [20,10]	2×10^9	4×10^{10}
Si [28,14]	1×10^{10}	2×10^{11}
Fe [56,26]	3×10^{11}	5×10^{12}
U [238,92]	2×10^{14}	3×10^{15}

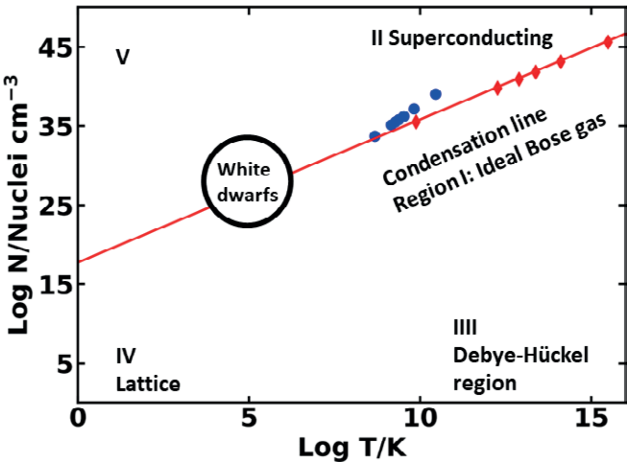

Figure 1. Number density (*N*) of stable nuclei vs. temperature phase diagram for the charged Bose gas. The condensation line shown use Eq. (4) and the data from Table 1. Adapted from Figure 1 in Ref. [1]. The data points from the unscreened model (Z from Table 1) are shown as red symbols while the results corresponding to Z=1 model are shown as blue symbols. We indicate schematically a region relevant for white dwarfs (large black circle) (from Figure 1 in Ref. [1]).

With even the lowest densities *N(He)*, the accompanying electron gas is highly relativistic and degenerate. We intend to go beyond these simple estimates using a screened intervening plasma including both magnetic and dielectric susceptibilities. Notably, the core temperatures for the seven ages of a $20M_o$ star discussed by Trimble are T = 1.9×10^8 K for a star with Helium as fuel element and T = 3.7×10^9 K for a star with Silicon as fuel element [18]. These numbers are in surprisingly good agreement with our estimates based on using Z=1 in Table 1.

In region I, near the condensation line, $\rho\sim\frac{6}{8\pi}\frac{Mk^3}{Z^6e^6}T^3$, the system is nearly an ideal Bose gas. Above the condensation line in region II (high density, high temperature), a rotating gas should become superconducting, Region III corresponds to the classical Debye-Hückel (high temperature, low density) region, and in region IV conditions are favourable for the formation of a lattice (low temperature, low densities). Region V (low temperature, high density), exhibits an energy gap (c.f. eq. (7)), where the quasi-particle elementary excitation energy has the form [1,12,13]

$$\varepsilon(p) = \sqrt{\left(\frac{p^2}{2m}\right)^2 + \left(\hbar\omega_p\right)^2}, \tag{7}$$

where ω_p is the classical plasma frequency.

A DIVERSION

With Bose Einstein condensation in stellar systems, further unanticipated complications may occur. As they contract under the influence of gravitational forces, their core densities and temperatures will increase, leading to charged Boson core regions with increasingly heavy fuel elements. Available nuclear mass models show that not all numbers of proton-neutron combinations would be stable. For each state there is a minimum and a maximum number of neutrons and protons that are stable: a phenomenon known as the neutron and proton drip line [22]. The nuclear mass models demonstrated that certain ensembles of protons and neutrons are inherently unstable. That is, the ground-state configurations of such species are energetically unstable to the emission of a constituent nucleon [22]. The matter is still open.

Even the established sign of nucleon-nucleon interactions which can be used for plausible models of Bose condensation with neutron pairing [2] has been questioned. The data dating back to Seaborg's work from which that conclusion was reached has never been questioned. See references in [23,24]. Be that as it may, the possibility that Bose condensation and consequent magnetic events of even quarks and other exotic objects in the cores of neutron stars has seriously been broached [25]. Returning to our main theme, Hurley-Walker *et al.* [3] speculated that their observations might be due to a compact rotating magnetar. However magnetars are made of neutrons, that is fermions. Our considerations apply to bosons. Our propositions might then be appropriate rather to the early stages of the collapse of one of a pair of rotating massive binary stars. This would be consistent with the very low frequency of the pulses.

CONCLUSIONS

Quantum coherent Bose-Einstein condensation is a general property of matter with particles of even spin. Therefore, it might reasonably be expected to play a role in astrophysics one way or another, just as Fermi-Dirac statistics does in the theory of white dwarf and neutron stars. Attempts to invoke Bose condensation and superconductivity are few [1-2]. The present proposal is unlike the original low temperature theories of superconductivity [10-11, 14-17]. It is concerned with a phenomenon that occurs with charge bosons at high temperature and high density [1]. The charged ideal Bose gas is superfluid below its critical point [1,12]**.** And a rotating superfluid has a Meissner effect [8-10] with consequent, expulsion and buildup of large magnetic effects. The observed linearly polarized ultra-long period low-frequency radio emission is known to be related to magnetic fields [5-7]. The Bose-Einstein condensation could be the origin of the magnetic fields and the phenomenon, not previously observed, might be of wider occurrence, as anticipated in [25] A. Mann, "The strange hearts of neutron stars", *Nature* **579**, 20-22 (2020).

ACKNOWLEDGMENTS

The authors thank the "ENSEMBLE^3 – Centre of Excellence for nanophotonics, advanced materials and novel crystal growth-based technologies" project (GA No. MAB/2020/14) carried out within the International Research Agendas programme of the Foundation for Polish Science co-financed by the European Union under the European Regional Development Fund and the European Union's Horizon 2020 research and innovation programme Teaming for Excellence (GA. No. 857543) for support of this work. The authors are grateful to Professor Nikolai Bunkin for drawing our attention to the work of Hurley-Walker and colleagues.

REFERENCES

[1] B. W. Ninham, "Charged Bose gas in astrophysics", Phys. Lett. **4**, 278 (1963).

[2] C. Gruber and A. Pelster, "A theory of finite-temperature Bose-Einstein condensates in neutron stars", Eur. Phys. J. D **68**, 341 (2014).

[3] N. Hurley-Walker, X. Zhang, A. Bahramian, S. J. McSweeney, T. N. O'Doherty, P. J. Hancock, J. Morgan, G. E. Anderson, G. H. Heald, and T. J. Galvin, "A radio transient with unusually slow period emission" Nature **601**, 526 (2022).

[4] M. Kramer, B. W. Stappers, A. Jessner, A. G. Lyne and C. A. Jordan, "Polarized radio emission from a magnetar", Mon. Not. R. Astron. Soc. **377**, 107–119 (2007).

[5] L. M. Capparelli, A. Damiano, L. Maiani, A. D. Polosa, "A note on polarized light from magnetars", Eur. Phys. J. C **77**, 754 (2017).

[6] S. Dai, M. E. Lower, M. Bailes, F. Camilo, J. P. Halpern, S. Johnston, M. Kerr, J. Reynolds, J. Sarkissian, and P. Scholz, "Wideband Polarized Radio Emission from the Newly Revived Magnetar XTE J1810–197", *ApJL* **874** L14 (2019).

[7] T. Hashimoto, Y. Ota, A. Tsuzuki, T. Nagashima, A. Fukushima, S. Kasahara, Y. Matsuda, K. Matsuura, Y. Mizukami, T. Shibauchi, S. Shin, K. Okazaki,

"Bose-Einstein condensation superconductivity induced by disappearance of the nematic state", *Sci. Adv.* 6 : eabb90 *(*2020).

[8] M. R. Schafroth, "Superconductivity of a charged ideal Bose gas", Phys. Rev. **100**, 463 (1955).

[9] J. M. Blatt, "Persistent ring currents in an ideal Bose gas", Prog. Theor. Phys. **26**, 761 (1961).

[10] M.R. Schafroth, S.T. Butler, and J.M. Blatt, "Quasi-chemical equilibrium approach to superconductivity", Helv. Phys. Acta 30, 93 (1957) .

[11] R. Friedberg., T. D. Lee, and H. C. Ren, "A correction to Schafroth's superconductivity solution of an ideal charged Boson system", Ann. Phys. 2**08**, 149-215 (1991).

[12] B. W. Ninham, "Charged Bose gas", Nucl. Phys. **53**, 685-692 (1964).

[13] L. L. Foldy, "Charged Boson gas", Phys. Rev. **124**, 649 (1961).

[14] J. Bardeen, "Theory of the Meissner Effect in Superconductors", Phys. Rev.**97** (6): 1724–1725 (1955).

[15] L. Cooper, "Bound electron pairs in degenerate Fermi gas". Phys. Rev. 104 (4): 1189–1190 (1956).

[16] J. Bardeen, L.N. Cooper, and J.R. Schrieffer, "Theory of Superconductivity", Phys. Rev. 108, 1175 (1957).

[17] N. N. Bogoliubov, "On a new method in the theory of superconductivity", Il Nuovo Cimento. 7 (6), 794–805 (1958).

[18] V. Trimble, "The origin and abundances of the chemical elements revisited", The Astron. Astrophys. Rev. **3**, 1-46 (1991).

[19] G. Burbridge and F. Hoyle, "The origin of helium and other light elements", Astrophys. J., **509**, L1-L3 (1998).

[20] F. Hoyle and W. A. Fowler, "Nucleosynthesis in supernovae", Astrophys. J. **132**, 565-590 (1960).

[21] K. M. Burbridge, G. R. Burbridge, W. A. Fowler, and F. Hoyle, "Synthesis of the elements in stars", Rev. Mod. Phys. **29**, 547-650 (1957).

[22] P. J. Woods and C. N. Davids, "Nuclei beyond the proton drip-line", Annual Rev. of Nuclear and Particle Science **47**, 541-590 (1997).

[23] O. K. Manuel, B. W. Ninham and S. E. Friberg, "Superfluidity in the Solar Interior: Implications for Solar Eruptions and Climate", Journal of Fusion Energy, (2003), 21 (3/4), 193- 198.

[24] O.K. Manuel ,C. Bolon and P. Jangam, "Nuclear systematics: II. The cradle of the nuclides", Journal of Radioanalytical and Nuclear Chemistry **251**, 417–422 (2002).

[25] A. Mann, "The strange hearts of neutron stars", *Nature* **579**, 20-22 (2020).