Astronomy Domine: advancing science with a burning plasma

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ABSTRACT

Inertial Confinement Fusion (ICF) is a subject that has been studied for decades, because of its potential for clean energy generation. Although thermonuclear fusion has been achieved, the energy out has always been considerably less than the energy in, so high energy gain with a burning thermonuclear plasma is still some way off. A multitude of new science has come from the ICF programme that is relevant outside the field (typically in astrophysics). What we look at in this text is what new science can come from the much more extreme conditions that would be created in the laboratory if a burning ICF plasma could be created - in terms of energy density the most extreme macroscopic environment ever created. We show that this could impact science from particle physics through astrophysics and on to cosmology. We also believe that the experiments that we propose here are only a small part of the science that will be opened up when a burning thermonuclear plasma is created in the laboratory.

KEYWORDS
ICF; astrophysics; cosmology; laser science

1. Introduction

This paper makes an assumption about the future: that we will have discovered how to ignite and burn[1] a small capsule of thermonuclear fuel in the laboratory. In fact, we know that this can be done through reports of data from nuclear testing (Broad 1988, Evans 2010 [2,3]); what we don't know for sure is how big a driver will be required and when such a machine will be built. There are currently two contender technologies that most people who work in this field believe stand a credible chance of driving a capsule to the conditions that are required to achieve thermonuclear burn. They are high-power lasers and pulsed power machines. The largest machines of both types are currently in two national laboratories in the United States. The Z-machine is the largest pulsed-power machine in the world (Savage et al. 2011 [4]) and is at the Sandia National Laboratory in New Mexico. The National Ignition Facility (NIF, Lindl et al. 2004 [5]) is at the Lawrence Livermore National Laboratory in California and is the

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[1] In this paper we use the term burning plasma to refer to a plasma that has ignited and has burnt a substantial fraction of its thermonuclear fuel, which is different to the definition in Betti et al., (2015) [1].

largest high-power laser in the world. Although the technologies are very different, both machines have the same aim: to take stored electrical energy (in capacitors), compress some of that energy in time, and deliver that power to a small space. Targets are then designed to amplify the energy density by delivering the energy to the thermonuclear fuel over a shorter time than applied to the target, further magnifying the large power per unit area input from the driver. In this way the required energy density (very high temperatures and densities) necessary for producing thermonuclear burn in the fuel is created.

Every time an amplification in power takes place - either in the driver or in the target - there is considerable inefficiency. A metric as to the overall success of the process is that the energy produced by the capsule from thermonuclear reactions is greater than the driving machine's stored energy (sometimes called wall-plug energy), or, less ambitiously, the energy delivered to the target, or less ambitiously still, the energy delivered to the thermonuclear fuel within the target. This latter has been achieved on the NIF (Hurricane et al. 2016 [6]), but the more ambitious goals have not, as of yet been achieved. Generally speaking, the larger the target the larger the drive energy needed, but the larger the target the easier it is to model its behaviour using numerical and computational models (Rose, Hatfield and Scott, 2020 [7]). As of the time of writing (July 2021) the NIF has recorded about 170kJ thermonuclear output energy, which far exceeds the energy delivered by NIF to the fuel (5-15kJ) but not the energy delivered to the target by the laser (1-2MJ). NIF is 'smouldering', but not yet alight. The original design aim was for the target to produce at least 10MJ thermonuclear output energy. The current question is whether using NIF as a driver we can produce this, or whether an upgraded NIF delivering more than 2MJ is required for the target to properly burn involving the initial hot-spot producing/driving a thermonuclear burn wave through the majority of the fuel. Note that output energy scales highly non-linearly with driver energy - once the plasma is ignited the energy output is expected to skyrocket. A few times bigger driver might potentially produce 100s-1000s of times more energy. There is a difference of opinion within the ICF community as to what energy is required to ignite a target (e.g. Rose, Hatfield and Scott 2020 [7], Randewich et al 2020 [8]). Currently the consensus is that 10MJ will probably allow this to take place, but potentially an energy less than this could work. Although modelling to predict the position of that cliff-edge has historically not been accurate, once the cliff has been ascended and thermonuclear burn has been ignited there is considerable confidence that the modelling of the implosion and burn is more accurate.

Alongside the goal of industrial power generation, high-power lasers also allow experiments to be undertaken through compression that replicate conditions (or some aspects of conditions) found in astrophysical or cosmological settings (Rose 2004 [9]). When thermonuclear burn happens a further, even greater amplification of energy density occurs than has been achieved in these 'laboratory astrophysics' experiments. This paper looks at what the amplification of energy density through thermonuclear burn can possibly achieve.

The conditions that are found in a burning thermonuclear plasma are extreme. Figure 1 shows that around the time of peak compression, in the deuterium-tritium (DT) fuel, temperatures of many tens of keV are obtained, with densities of many hundreds of g/cc. The main energy output is in the form of high energy neutrons; indeed in all schemes that look at using the energy output, the neutrons that generally escape the plasma are captured and converted to heat in some way. There have been a number of suggestions to use this high neutron flux for scientific applications (Taylor

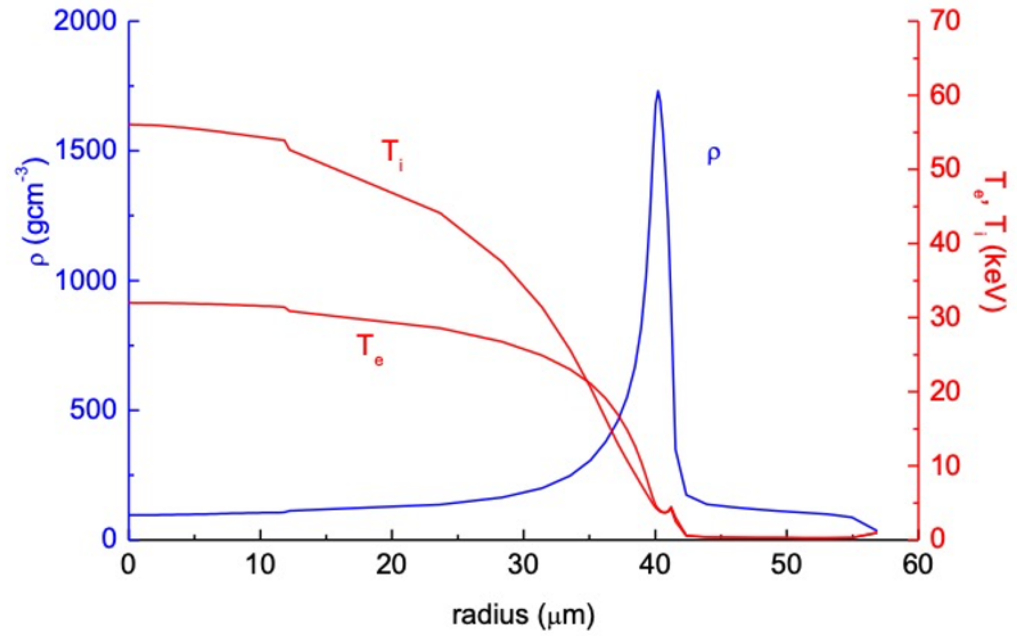

Figure 1. Density, electron and ion temperatures in compressed DT at peak compression (adapted from Djaoui 1996 [13]).

et al, 2007 [10]) but the authors believe that it is the generation of X-rays from the burning fuel that offer the greatest scope for 'blue sky' scientific advance. Figure 1 does not show the radiation field in the capsule and we use the calculations of Rose (2013) [11] to give some indication of the radiation fields generated in burning thermonuclear fuel. We consider three balls of plasma of uniform composition, density and electron temperature, the first representative of a burning DT plasma and the second and third representative of burning D plasmas. The sizes and conditions (material density and temperature) are representative of a burning NIF target and of advanced D-burning capsules as described by Tabak (1996) [12] as depicted in Figure 2. We include the burning D capsules not because we believe that pure deuterium burning will be achieved soon (D burning has a number of practical advantages in terms of use at an industrial power plant, but is more challenging to achieve than DT burning) but rather to illustrate the far-future of the field and the opportunities that would be derived. Figure 3 shows simplified estimates of how intense the radiation field in the burning fuel becomes and how inclusion of different processes in the modelling affect the prediction of the field.

In none of these cases is the radiation field in equilibrium with the material and the spectra shown cannot be fitted with a black-body. However to give the reader an idea of the strength of the radiation field, the energy density in the field is equivalent to a black-body with a temperature of around 4keV for the DT and 14keV and 21keV for the D-burning capsules. This should be seen in comparison with the radiation field in a hohlraum heated by the NIF laser of at most 400eV. Because the energy density scales as T^4 the burning plasma radiation fields are vastly higher than what can be achieved by the laser alone. It is this extraordinary amplification of energy density

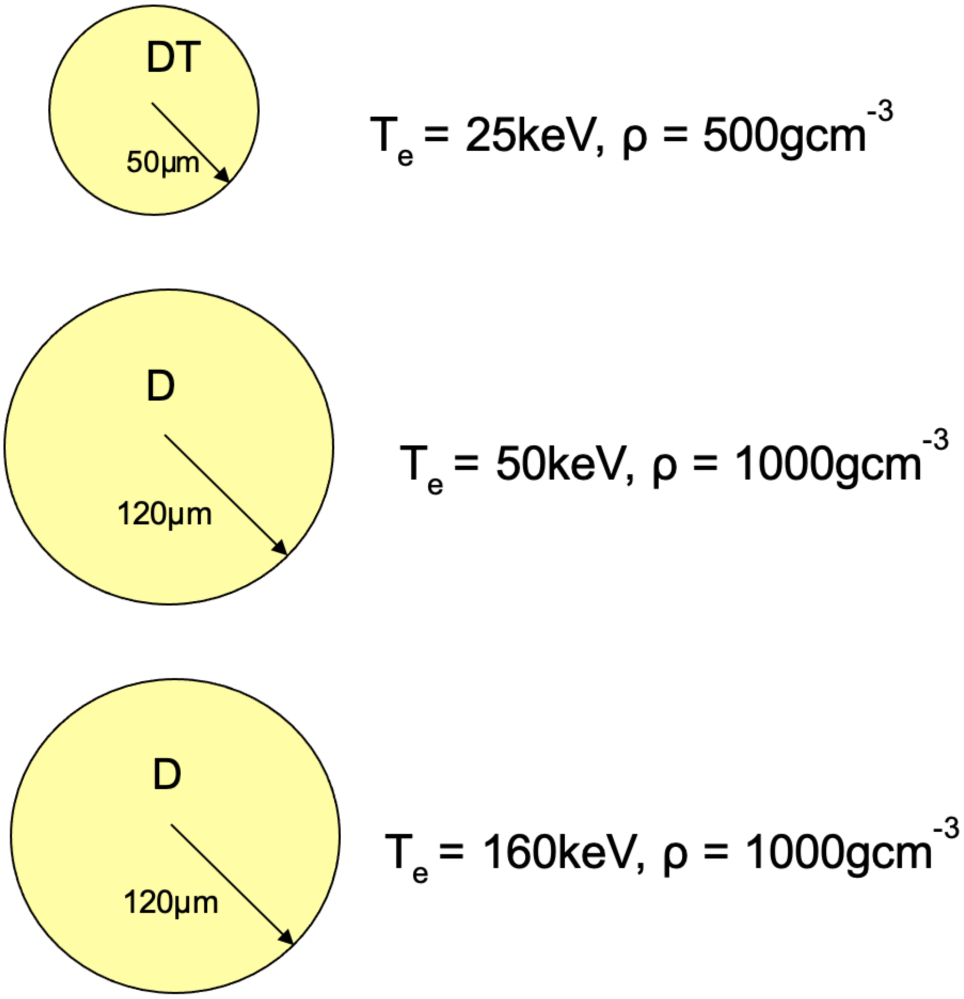

Figure 2. The spherical balls of uniform plasma considered in the simplified calculations of the radiation field (Rose 2013 [11]). The upper case (a) is that of a DT plasma, representative of the conditions in a burning plasma at the NIF. The other two-cases represent next-generation experiments, (b) and (c) respectively, in which we have learnt how to ignite a D-only plasma (as calculated by Tabak 1996 [12]).

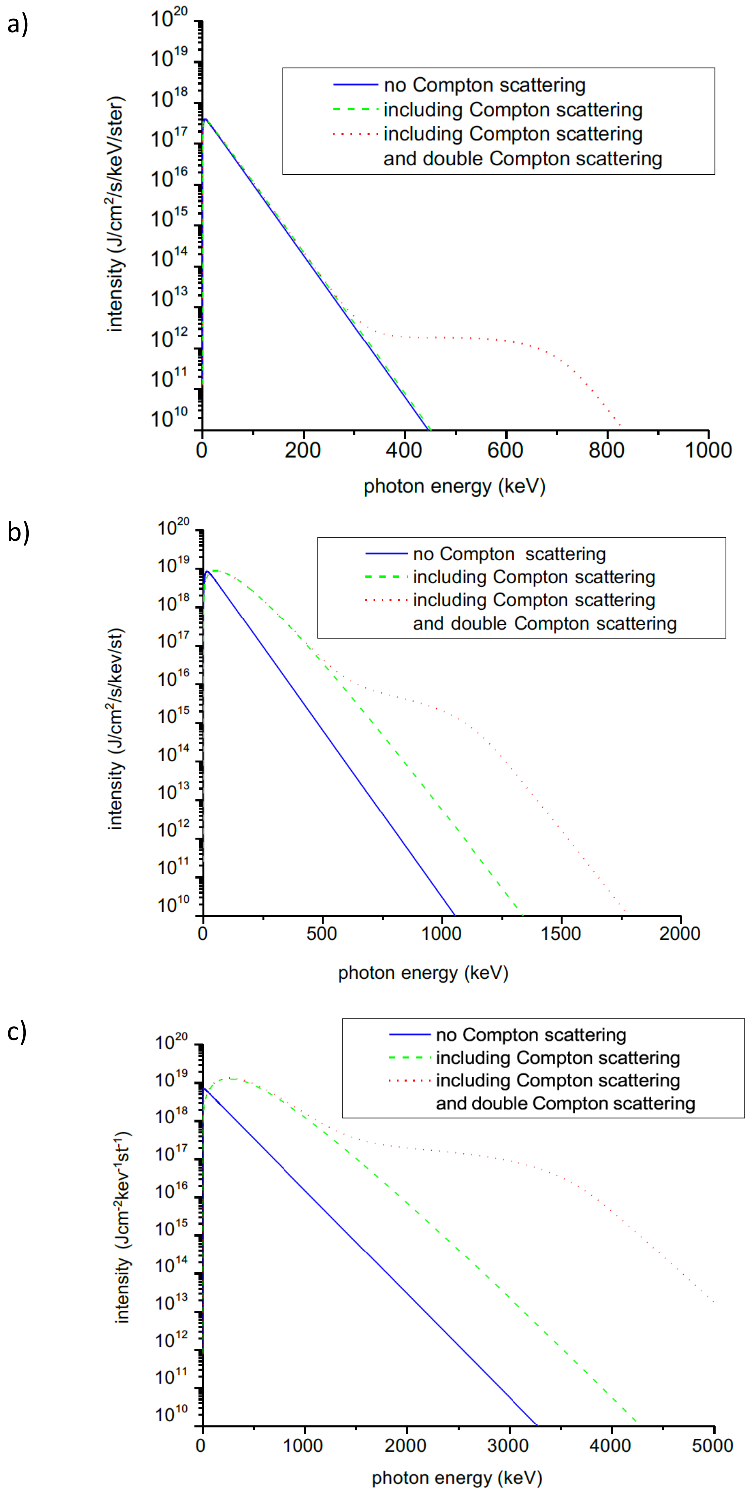

Figure 3. Upper sub-figure: Radiation intensity calculated for plasma (a) in figure 2, showing the effect of inclusion of different processes that couple radiation to matter (Rose 2013 [11]). Middle sub-figure: Radiation intensity calculated for plasma (b) in figure 2, showing the effect of inclusion of different processes that couple radiation to matter (Rose 2013 [11]). Lower sub-figure: Radiation intensity calculated for plasma (c) in Figure 2, showing the effect of inclusion of different processes that couple radiation to matter (Rose 2013 [11]).

that allows us to suggest the experimental opportunities in the rest of this paper.

2. Potential experiments within the burning plasma

2.1. Compton scattering (the Sunyaev-Zeldovich effect)

The Sunyaev-Zeldovich (SZ) effect (Sunyaev and Zeldovich 1972 [14]) predicts that the microwave background radiation spectrum traversing a hot ionized plasma will be characteristically altered due to inverse Compton scattering by the hotter free electrons in the plasma. This was a simple but a hugely powerful prediction which has been used over many decades to understand the large-scale structures in the Universe, particularly galaxy clusters. Use of the Sunyaev-Zeldovich effect has grown, particularly in the last few years with the new South Pole Telescope, the Atacama Cosmology Telescope, and the upcoming Simons Observatory all undertaking Sunyaev-Zeldovich Effect surveys as core parts of their science programmes. The Sunyaev-Zeldovich effect has proved to be one of the most powerful tools that we have for understanding the structure of the Universe on cosmological scales, particularly when combined with other probes e.g. gravitational lensing. In addition to being the process behind the SZ effect, Compton and inverse-Compton scattering in a thermal plasma has been proposed as operating in a number of astrophysical objects (Pozdnyakov, Sobol and Sunyaev 1977, 1979, 1983 [15–17]). Because Compton scattering plays such an important role in determining the radiation field, particularly in burning D plasmas, the study of the radiation field produced in such a burning plasma would potentially be of interest as a benchmark test for the modelling of Compton scattering in astrophysical modelling.

One effect that has the potential for study in a burning plasma is the modification of the SZ effect through different electron distributions. Challinor and Lasenby (1998) [18] have calculated relativistic corrections to the SZ effect by studying relativistic corrections to Compton scattering (although it should be noted that similar theoretical work was undertaken by Woodward, 1970 [19] thirty years earlier - although not applied to the SZ effect). The electron temperatures found in burning plasmas (many 10s of keV) exceed those even in the hottest intra-cluster media (around 10keV) and the effects of relativity on Compton energy exchange could potentially be detected and studied.

2.2. Double-Compton scattering (CMB in early Universe)

Our understanding of the evolution of the early Universe has been greatly influenced by measurements, with increasing precision, of the Cosmic Microwave Background radiation. The most recent measurements have shown that the spectral shape of the CMB is a black-body to high accuracy:

$$I(\epsilon) = \frac{2\epsilon^3}{(hc)^3}\left[\frac{1}{\exp(\epsilon/kT_\mathrm{e}+\mu)-1}\right]$$

$$\mu < 3\times 10^{-4}$$

The closeness of the CMB to a perfect black-body has been used to draw limits on the injection of photons into the radiation field in the early Universe providing we have an accurate model of the thermalisation process, and in particular the thermalisation rate, in the early universe. Originally the fastest thermalisation rate was thought to be inverse-bremmstrahlung - but from around 1980 it was realised (Thorne 1981 [20]) that a more obscure process, Double Compton scattering, was faster. Double Compton scattering is a similar process to bremsstrahlung/inverse bremsstrahlung but with the ion replaced by a photon. Both processes can exchange energy between the radiation field and the electrons in the plasma resulting in both radiation and electron distributions characterised by the same temperature (Compton scattering also achieves this, but alone it cannot lead to a thermal black-body spectrum). The inclusion of Double-Compton scattering in calculations of the spectral shape of the radiation field in the early Universe as it evolves was first done by Hu and Silk (1991, 1993) [21,22] and calculations have since been refined (Chluba 2005, Chluba and Sunyaev 2012 [23,24]). Although the double Compton scattering process has been studied, initially theoretically by Mandl and Skryme (1952) [25] and experimentally in accelerators (McGie, Brady and Knox 1966 [26]), no measurements have been made in the laboratory that are in any way comparable to what happens in the early Universe. Double-Compton scattering may leave a signature at high energy in the output spectrum from a burning NIF capsule, which opens the possibility of studying this elusive astrophysical process in a burning thermonuclear plasma.

2.3. Electron-positron production in plasmas (fundamental QED)

Electron-positron pairs are produced by a variety of processes in both the astrophysical and laboratory settings. In laboratory plasmas accelerated electrons can produce pairs either by direct interaction with the electric field of a nucleus (the Bethe-Heitler process) or by production of a photon in that interaction that then goes on to interact with a second nucleus to produce the pair (the Trident process) (see Jiang et al 2021 and references therein [27]). Another process, the interaction between two photons, can produce an electron-positron pair (the Breit-Wheeler process, Breit and Wheeler 1934 [28]). The process has been observed with virtual photons, for example an electron-positron pair is created through scattering of a photon from the electric field of a nucleus (Delbruck scattering). With real photons the non-linear analogue has been observed, where a gamma ray interacts with a propagating photon-bunch (Burke et al., 1997 [29]). However, the Breit-Wheeler process by which two real photons collide and create an electron-positron pair (creating matter from light) has never been observed in the laboratory. A number of schemes have been put forward to detect the BW process using high-power lasers (Pike et al, 2014, Ribeyre et al, 2016 [30,31]). The proposed scheme of Pike et al (2014) [30] (for which a credible platform has been designed and tested, Kettle et al., 2021 [32]) involved a beam of γ-ray photons produced by sub-picosecond pulse lasers interacting with keV X-ray photons generated by nanosecond pulse length lasers. The large number of positrons predicted by Pike et al (2014) [30] assumed that a NIF scale laser would provide the radiation field if coupled to an efficient current laser-generated gamma source (which would need a new sub-picosecond auxiliary laser synchronised with the 10s of nanosecond beams on NIF). The radiation field generated by a burning plasma would exceed that produced by NIF alone and so then copious BW electron positron pairs would be expected.

The Breit-Wheeler process is believed to be important in a variety of extreme astrophysical situations, including the well-known upper limit that it sets to the energy of a photon traversing cosmic distances through its interaction with the Cosmic Microwave Background (the CMB), and the Extragalactic Background Light (the EBL, from extragalactic sources), Nikishov (1962), Gould and Shréder (1967) [33,34]. However recently anomalies in this interpretation have been reported (Abdalla and Böttcher 2018 [35]), requiring either i) non-Standard Model Physics, ii) highly unusual unphysical gamma ray spectra from AGN or iii) modifications to our understanding of the EBL. Electron-positron pairs are also involved in the modelling of accretion disks around Active Galactic Nuclei (Bonometto and Rees 1971, Inoue et al 2019 [36,37]), and in pair-instability supernovae (Fowler and Hoyle 1964, Barkat, Rakavy and Sack 1967, Farmer et al 2019 [38–40]). The most recent interest involves linking pair-collapse supernovae with binary black-hole merger mass-gap observations from gravitational wave surveys (Farmer et al 2019 [40]).

Calculations (Rose 2013 [11]) suggest that, in addition to the processes involving electrons and nuclei in the plasma, in the NIF burning plasma the radiation field is so high that the Breit-Wheeler process would operate with both photons coming from the same radiation field (Rose 2013 [11]) - no need to also have an independent gamma source radiating through the field. There are also opportunities to increase the radiation field in the gamma range by accounting for the 16.75MeV gammas that are produced in a small proportion of DT reactions (Hill and Rose, 2014 [41]). Positron number densities produced by the Breit-Wheeler process approaching 10^{23}cm^{-3} are predicted for the most extreme pure deuterium burning radiation fields which is close to the electron number density in solid matter although still well below the electron number density in the plasma (Figure 4). It should also be noted that electrons and positrons are the dominant form of matter density for the period of the early Universe in which nucleosynthesis takes place (Figure 5) and although recent calculations (Wang et al 2011 [42]) suggest that their effect on nuclear synthesis rates through shielding is not large, burning plasmas offer the only credible way of experimentally investigating that.

3. Potential experiments that use the output from a burning plasma

3.1. Opacity experiments at high temperatures and densities (Sun centre, centres of other stars)

In a previous article (Rose 2004 [9]) in this journal the author looked at the possibility of using NIF to create plasma similar to the conditions found at the centre of the Sun to undertake an opacity experiment. The proposal involved producing material near 100g/cc using a cylindrical implosion, and then heating the compressed plasma to near 1keV using short-pulse heating. The experiment has not been undertaken, in part because the short-pulse heating envisaged has not been available. In addition, the technique relied on developing an improved understanding of the heating by fast electrons which was expected because of the development of fast-ignition (Norreys et al 2000, Kodama et al 2001 [43,44]). However, developments in fast-ignition have slowed and an experiment to look at the opacity under extreme conditions is now more likely to take place using the radiative output from a burning plasma. Current opacity experiments use X-ray radiation from a laser or pulsed-power source, either using absorption and emission spectroscopy, or measuring a transit time for a radiatively-driven wave (Bailey et al 2015, Hoarty et al 2019 [45,46]). Both kinds of experiments

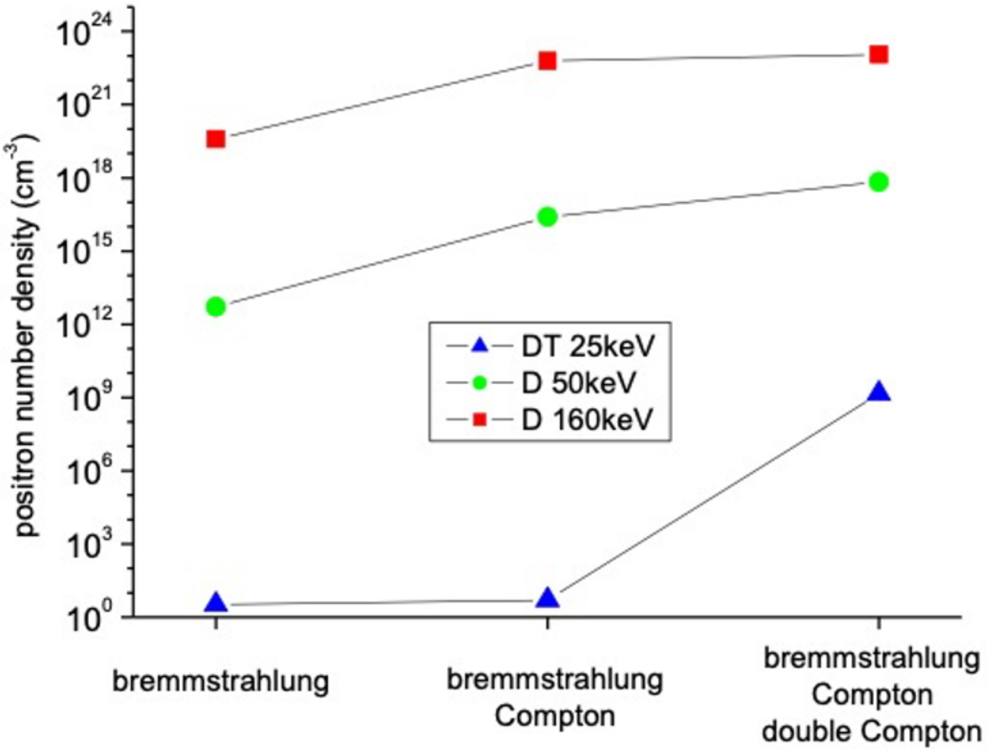

Figure 4. Steady-state positron number density from the two-photon Breit-Wheeler process for the three cases studied, showing the effect of inclusion of different processes that couple radiation to matter (Rose 2013 [11]).

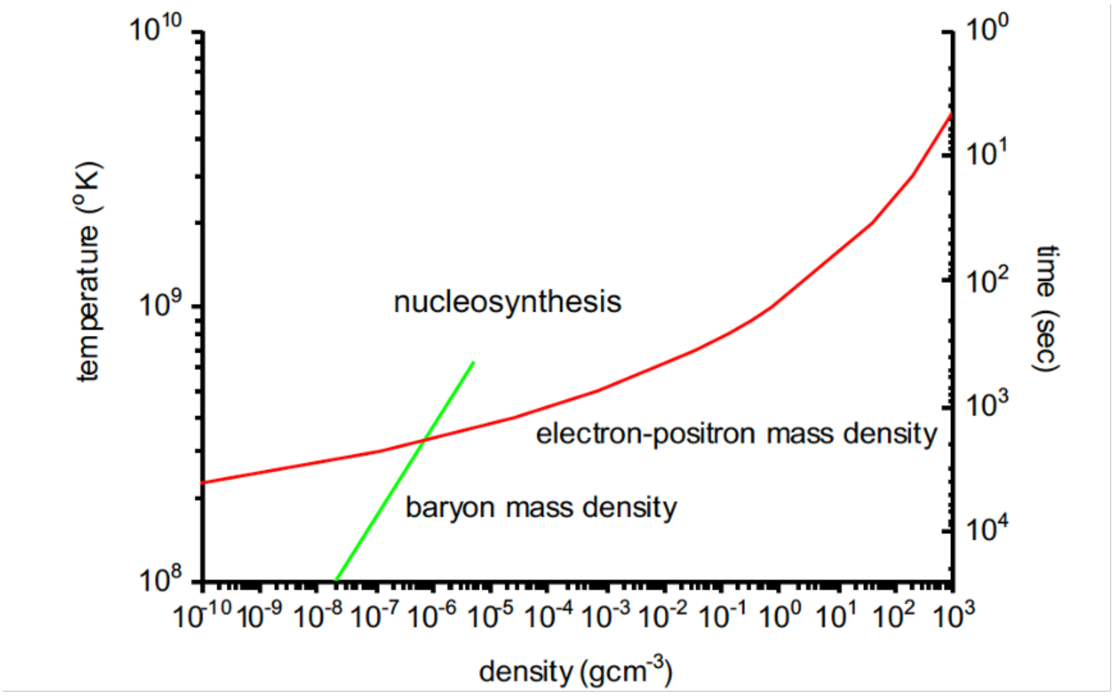

Figure 5. Density and temperature conditions in the early universe.

are limited in the temperatures that they can reach (typically below a few hundred eV), however much higher temperatures could be accessed using the high radiation fields from burning plasmas. Neither of these techniques however can access densities higher than solid, but to obtain those conditions it may be possible to use the radiative output from a spherically compressed burning plasma, where the opacity is measured by absorption spectroscopy through differing dopants in the capsule shell. Over the course of the implosion the shell samples a number of conditions of temperature and density which would allow multiple opacity measurements to be made that test a variety of extreme conditions (temperatures of many keV and densities many times solid density). Diagnosing the conditions in the shell will entail the use of high-Z K-shell dopants, where the temperature and density are determined using absorption and emission spectroscopy (this idea is quite old; Hauer et al used absorption spectroscopy as a diagnostic of shell conditions in 1986 [47]). These experiments would give us access to the conditions found in the centre of our Sun and also at the centre of many other stars at different evolutionary stages, within the laboratory.

3.2. Photoionised plasmas (compact objects, e.g. black holes)

There have been a number of experiments using high-power lasers and pulsed-power machines which have attempted to create plasmas in the laboratory that are photoionisation-dominated. These are plasmas in which the broadband radiation field is so intense that the ionisation rate is dominated by photoionisation, rather than electron collisional ionisation. They are thought to occur near compact objects where the accretion of material creates such a high temperature that the plasma radiates strongly. The spectra of such objects have been observed in the X-ray region for many years using X-ray satellites such as Chandra and XMM-Newton, and the spectra are used to understand the conditions near the compact object. Future X-ray telescopes, such as ESA's Athena are planned to extend these measurements (Mehdipour, Kaastra, and Kallman 2016 [48]). Because of these recent experiments, atomic and radiation models (for example the code CLOUDY, Ferland et al 2017 [49]) are starting to be compared to experimental data, but the radiation fields produced in the laboratory to date are not sufficiently intense to check the modelling when applied to the most extreme photoionised astrophysical environments (e.g the neighbourhoods of supermassive black holes in Active Galactic Nuclei, AGN - quasars). The parameter that is discussed in the astrophysical literature (starting with Tarter, Tucker and Salpeter 1969 and Tarter and Salpeter 1969 [50,51]) as characterising a photoionised plasma is

$$\xi = 4\pi F/n_\mathrm{e}$$

where F is the radiation flux and n_e is the electron number density. Fujioka et al (2009) [52] used the GEKKO XII laser to achieve ξ=9 erg cm s^{-1} and several experiments on the Z-machine at Sandia National Laboratory (Foord et al 2004, Loisel et al 2017 and Mancini et al 2020 [53–55]) have achieved peak values of ξ=20-60 erg cm s^{-1} which does replicate some astrophysical plasmas such as neutron-star binaries with ξ 10^{-1}-100 erg cm s^{-1} (Torrejón et al. 2015 [56]) whereas the most extreme astrophysical cases such as quasars are thought to operate at or above ξ=1000 erg cm s^{-1} (Danehkar et al. 2018 [57]). Laboratory experiments have been challenging because astrophysical photoionised plasmas have low enough densities that photoionisation is balanced by radiative and dielectronic recombination (both are two-body processes rather than three-body recombination which dominates at the usual densities obtained in laser-produced plasmas). At these low-densities it takes many nanoseconds for plasma photoionisation and recombination to achieve a steady-state, which characterises astrophysical photoionised plasmas. It is challenging to create an intense radiation field in the laboratory that has such a long duration, although plans involving multiple empty hohlraums (metal cans to convert laser beams to x-rays) driven by the NIF laser have been put forward (Mancini 2021, private communication). Calculation of the radiation field from a burning NIF capsule are so much higher than can be created by a laser alone that it suggests that ξ values higher than achieved to date would be possible, extending the range of astrophysical objects for which atomic and radiation modelling can be validated. The radiation field from a burning plasma does not have the time-duration that is needed for a steady-state however - it remains to be seen whether it will be possible to extend the radiation field duration from a burning plasma through advanced hohlraum design. One recent development is the realisation that the astrophysical photoionised plasmas cover a larger range of densities (Garcia et al, 2016 [58]) than originally considered and the higher densities involved require shorter equilibration times which makes the issue of extending the radiation field from a burning plasma less severe.

3.3. Thermal Schwinger QED physics (non-perturbative QED and strong-field physics)

Schwinger (1951) [59] predicted that a sufficiently strong electric field could produce electron positron pairs from the vacuum. However this would require an electric field that lies well beyond current experimental high-power laser capability (Turcu et al 2016 [60]). Recently Gould et al (2018) [61] have noted that the electric fields that can

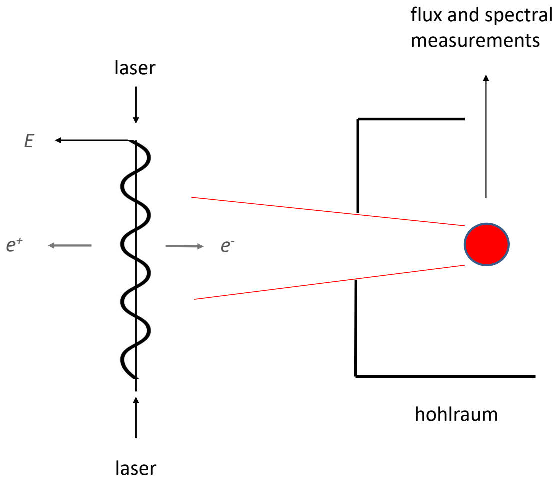

Figure 6. A schematic diagram of the thermal Schwinger experiment, see also figure 4 of Chen et al., (2014) [67].

be created at the focus of current ultra-high intensity lasers beams, when bathed in an intense radiation field, such as that produced in a burning plasma, can in theory produce electron-positron pairs from a thermally augmented Schwinger mechanism (Figure 6). Moreover, the rate at which this is predicted to occur comes from a non-perturbative result involving all-orders and all-loops in QED (Gould and Rajantie 2017a, Gould, Rajantie and Xie 2018 [61,62]). Any experimental verification of this pair-production rate (which is orders of magnitude faster than the perturbative QED estimates) would carry across to strongly-coupled physics and would show that the technique could be used in calculations involved in the search for magnetic monopoles. Magnetic monopoles, as postulated by Dirac (1931) [63] have never been observed but are an intense area of current study (Rajantie 2012 [64]). The most likely environments in which they may be detected are thought to be in heavy-ion collisions at the LHC (Acharya et al 2017 [65]) and in neutron star mergers (Gould and Rajantie 2017b [66]). So the very high radiation fields produced in burning plasmas may be able to validate new theoretical techniques of non-perturbative calculations which could be used in the search for magnetic monopoles.

3.4. Line-coincidence photopumping (astrophysical X-ray lasing)

High-Z material mixed with the DT typically makes it harder to achieve burning in inertial confinement fusion because the higher-Z material radiates away the energy in the fuel, increases the heat capacity, and dilutes the number density. However, if the burn is robust enough to tolerate a small amount of high-Z material, the extra emission may provide a useful diagnostic of the conditions in the plasma. Figure 7 shows a simplified calculation of the radiation field in the DT plasma shown earlier, but including a small admixture of Kr (Xu and Rose 2000 [68]). Under the conditions chosen the Kr is ionised to H-like and He-like and the Kr line emission is seen to exceed the background generated by the DT emission. In this way the burning thermonuclear fuel is providing an extremely intense line photon source. This could be used for a

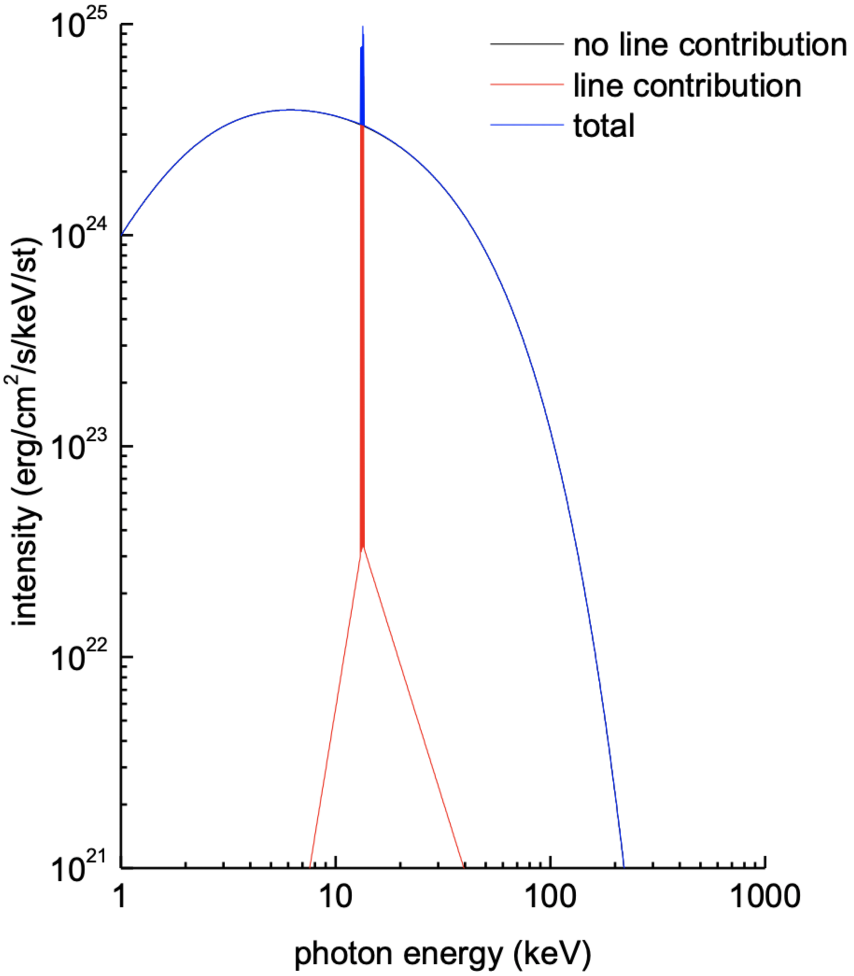

Figure 7. Intensity of radiation from a sphere of DT (the top capsule in figure 2), doped with Kr at a number density of 0.0001 showing the contribution of Kr line radiation (Rose 2000 [68]).

number of applications, but the one considered here is the possibility of pumping a line-coincidence scheme in another ion in a separate plasma. This work would be part of ongoing experimental work that explores in the laboratory mechanisms by which XUV and X-ray lasing can occur in plasmas (Hobbs et al 2020 [69]).

The shortest wavelength laser to have been seen in an astrophysical setting is driven by line-coincidence photopumping (Letokhov and Johansson 2009 [70]). and operates in the optical region. Could such a mechanism produce an XUV- or X-ray laser? An experiment to create such a laser in the laboratory, pumped by a burning plasma, would help us understand whether this is feasible. On a more speculative note, if it can be shown that XUV / X-ray lasing is practically impossible in any credible natural astrophysical environment, then any explanation for an astronomical observation of X-ray lasing might have to include intelligent creation of the laser (a form of Optical SETI, Abeysekara et al 2016 [71])!

4. Conclusions

In this paper we have looked at outlines of new classes of experiment that may be possible when burning inertial confinement fusion plasmas become a reality. However, as is often the case when moving several orders of magnitude into a novel regime, the most exciting discoveries are likely to be completely new phenomena that are not yet imagined. Although historically a key focus of achieving the goal of a burning plasma has been as a step towards a fusion power plant, we have looked at using the achievement (in particular the resulting intense radiation field) for fundamental science. Discovery Science at NIF (for example Fournier et al., 2019 [72]) has been hugely impactful in a number of areas of fundamental physics - the same opportunity should not be missed for a burning plasma successor. Furthermore, many upcoming astronomical projects (for example the Simons and Athena Observatories) require sophisticated modelling of physics that can only be directly observed with a burning plasma. The conditions in a burning plasma are so extreme that they lend themselves to exploration in the laboratory of situations only otherwise encountered in astrophysics (and some not even there - we will be able to create completely new regimes of matter and radiation not found in nature). To make the most of a burning plasma platform, such a facility should include flexibility and instrumentation for both energy production and discovery science. We have seen that experiments relevant to many aspects of astrophysics and cosmology of current interest may be possible and certainly deserve further study to assess their potential. Achieving a burning plasma in the laboratory would be a huge scientific milestone - this paper sets out where at least the authors would like to go after that, and we hope that within a few years our community will be looking seriously at some of the possibilities we have discussed.

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