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Lithium synthesis around stellar mass black holes

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Abstract: We present a study of nucleosynthesis of light elements in the accretion disk of stellar mass black holes. The amount of both stable isotopes of lithium produced is sizeable for a host of values of black hole mass, disk viscosity and accretion rate. We discuss our results in the context of the lithium problem and propose observational tests for this mechanism.

Keywords: black holes, lithium problem, nucleosynthesis, microquasars

1 Introduction

Lithium is one of the very few elements in our Universe whose abundance is significantly affected by big bang nucleosynthesis (BBN), nuclear spallation processes in cosmic rays, and stellar nucleosynthesis. In particular, its ^{7}Li isotope is observed in the atmosphere of relatively cold stars in our Galaxy, namely halo stars of varying metallicity and stars belonging to globular clusters. The very first observations [1] have revealed a remarkable flat trend in the abundance of ^{7}Li vs the metallicity of the target star, known as the "plateau"; the most recent observations of halo stars (see [2] and references therein) show instead a clear "meltdown" of such single abundance value at the lowest metallicities, as well as a moderate, yet non-negligible dispersion at intermediate ones. The "roof" of this plateau still sits at a factor $\sim$3 below the prediction from standard BBN, a discrepancy that is known as the "lithium problem". If the value of the plateau is of primordial origin, the observations are almost impossible to reconcile with standard BBN, and exotic models are to be invoked [4, 5]. If that value is the result of processes of stellar origin, it *is* possible to set up a stellar mechanism able to deplete the original abundance, but it is still left to demonstration how this mechanism can act over three orders of magnitude in the metallicity of the star, thus reproducing an almost flat envelope. Cosmic-ray spallations can also destroy ^{7}Li, but it seems unlikely that they can reproduce the observed features. See [3] for state-of-the-art reviews.

In a recent paper [6], we have added another piece to the lithium problem, opening up a scenario which needs to be taken into account in future studies concerning this subject. The existence of stellar mass black holes accreting from companion stars is established through observations of so-called microquasars, visible in X-ray frequencies in our Galaxy [7]. We show that material accreting onto a stellar mass black hole from a companion star, in a disk with characteristics of a hot torus, can undergo nucleosynthesis, and produce sizable quantities of light elements. In the following we summarise the results of our recent study, showing how our results could in principle be worsening the lithium problem.

2 Accretion onto black holes

Accretion onto black holes in the form of hot tori was originally proposed in [8] to account for radio jets in some active galactic nuclei. Consider a black hole of mass M_{BH} accreting at a rate $\dot{M}$ through a disk of half-thickness $h(r)$. The momentum transfer is driven by a viscous stress of the form $f_\phi = \alpha P$, which leads to a radial inflow timescale $t_r(r) = \alpha^{-1}(r/h)^2(r/r_g)^{3/2}r_g/c$, where $r_g = GM_{BH}/c^2$. The core idea behind the hot torus model is to conceive an accretion configuration in which the inflow timescale t_r is short enough as to prevent electrons and ions from coupling. This is achieved for low accretion rates, specifically [8] $\dot{m} \equiv \dot{M}c^2/L_{Edd} \lesssim 50\alpha^2$, where L_{Edd} is the Eddington luminosity. In such regime the frictional heat is not efficiently radiated away but is stored, the accretion region is inflated to an ion pressure supported torus with $h(r) \simeq r$ and ions remain at the virial temperature, $k_B T = (r_g/r)m_p c^2/3$. It is therefore not unnatural to reach ion temperatures of tens of MeV in the hot torus. Moreover, the mean mass density is $\rho(r) = \alpha^{-1}\dot{m}(r/r_g)^{-3/2}3m_p/(2\sigma_T r_g)$. Following [9] we take the hot torus to extend from $r_i = 100r_g$ down to $r_f = 6r_g$. Notice that the hot torus is optically thin and not in local thermodynamic equilibrium – the gas density is in fact lower and the temperature higher than in standard thin disks, suppressing free-free opacity. The main sources of photons in the torus are electron radiating processes, in particular bremsstrahlung. For further details see Ref. [6].

It is clear from the discussion above that extremely high temperatures are reached inside the torus and nuclear reactions can take place. In particular, reactions with thresholds of MeV and above – unimportant in environments such as BBN or the cores of main sequence stars – are easily triggered. This is for instance the case of $\alpha + \alpha$ reactions, especially important for the synthesis of light elements as pointed out in [10, 9]. We use NetGen [11] and NNDC [12] to identify and parametrise all reactions (including photodissociations) relevant for ^{6}Li, ^{7}Li and ^{7}Be at the hot torus temperatures, cross-checking with other nuclear data compilation such as [13] where possible. Next, the Boltzmann equations for the abundances of these isotopes are solved setting the initial abundances of light elements to the ones leftover by BBN. For a given set $(M_{BH}, \dot{M}, \alpha)$ we solve the three coupled differential equations between $r_i = 100r_g$ and $r_f = 6r_g$, and compute the isotope masses in the (steady-

state) accretion torus at any given moment as well as the total expelled mass after an interval of time Δt and given a fraction of expelled material f_{exp}. We adopt $\Delta t = 100$ Myr and $f_{exp} = 0.5$ all along, but our results can be trivially scaled to other values.

3   Results

The lithium output for sample black hole masses of 1 $M_\odot$ and 100 $M_\odot$ are shown in figure 1 in the plane α vs $\dot{M}$. It is clear that the nucleosynthesis in the hot torus can produce significant masses of ^{7}Li (plus ^{7}Be) and ^{6}Li, regardless of the black hole mass. On the other hand, the Eddington limit $L \equiv \varepsilon \dot{M} c^2 \leq L_{Edd}$ – indicated by the shadowed area in figure 1 with typical black hole accretion efficiencies $0.06 \leq \varepsilon \leq 0.42$ – does depend on M_{BH} and sets the most stringent constraint on the achievable amount of isotopes. Masses as large as 10^{-2} $M_\odot$ are reached for hundred solar masses black holes. For the case of a 5 $M_\odot$ black hole, the lithium is produced at a ratio ^{6}Li$/(^7$Li$+^7$Be$) \simeq 0.25 - 0.29$.

The nuclear reactions leading the synthesis of the lithium isotopes are the $\alpha + \alpha$ reactions: ^{4}He$(\alpha,n)^7$Be, ^{4}He$(\alpha,p)^7$Li, ^{4}He$(\alpha,d)^6$Li and ^{4}He$(\alpha,np)^6$Li. All present similar thermally averaged cross-sections at the temperatures of interest and yield similar outputs of ^{6}Li, ^{7}Li and ^{7}Be as shown in figure 1. Therefore, the final abundance of lithium is sensitive mostly to the content of ^{4}He present in the plasma. We find that in order to suppress lithium production by a factor $\sim 10^4$ it is necessary to suppress the original abundance of ^{4}He by a factor 10^2 (notice that the helium abundance enters quadratically in the Boltzmann equation). Varying the initial abundances of D, ^{3}H and ^{3}He negligibly affects the final results, and adding an initial abundance of neutrons up to half of the number fraction has no significant effect. These checks show that the synthesis in the hot torus is sensitive mostly to its physical properties rather than the initial conditions of the gas chemistry (modulo the abundance of ^{4}He, which is the fundamental reactant for our purposes). It is worth stressing that synthesis at this level is possible because of the short resilience time of elements inside the hot torus. The timescale for photodissociation of ^{6}Li, ^{7}Li and ^{7}Be is much larger than the inflow timescale at the relatively low photon densities considered here, and even more so for photodissociations with higher thresholds –such as for ^{4}He– given the increasing paucity of photons at higher energies (see however [14] for a different case).

4   Implications and outlook

The amount of ^{7}Li and ^{6}Li produced by primordial nucleosynthesis, according to the most recent estimates of baryon density, are ^{7}Li/H $= 5.24 \times 10^{-10}$ and ^{6}Li/H $= 10^{-14}$; this represents the minimal "background" level of lithium isotopes which are present in the Galaxy at the time of its formation. In light of these figures, our results have interesting implications for the lithium budget.

First, it is expected that 10^9 stellar mass black holes are present in our Galaxy. The Milky Way mass in stars and gas is $M_{gal} \sim 5 \times 10^{10}$ $M_\odot$, which means that in principle, if a typical hot torus produces 10^{-4} $M_\odot$ of both ^{7}Li and ^{6}Li, then only 0.1% (10^{-6}%) of the microquasars in our Galaxy

need to host a hot torus so that the synthesised amount of ^{7}Li (^{6}Li) is comparable to the BBN "background" level.

Second, the first generation of stars (Population III, Pop. III) is expected to form in small halos of total baryonic mass 10^5 $M_\odot$. Recent numerical simulations of early star formation show evidence for multiple Pop. III systems, with fragments of masses ranging in the sub-hundred solar masses regime. It has already been proposed that such systems may give rise to microquasars: what we wish to highlight here is that the production of 10^{-4} $M_\odot$ of ^{7}Li and 10^{-9} $M_\odot$ of ^{6}Li by *a single* microquasar is enough to equate the BBN "background" level in the halo where the Pop. III system has formed. These numbers are indeed achieved within the parameter space scanned in our study.

The previous examples are defective in some regards. In order for the quoted numbers to be taken at face value the material synthesised in the hot torus and expelled must be assumed to efficiently mix in the interstellar medium. This might be the case of primordial star-forming halos – where extremely efficient internal mixing is expected –, but not of the Milky Way, which raises the issue of even higher concentrations of lithium isotopes locally, around the microquasars themselves and in regions where microquasars are more frequent. Also, although it is not unreasonable that a significant part of the material gets expelled from the torus, presumably some of the expelled material would cross cool regions where significant spallation may occur. Finally, light element photodissociation within the torus can be important if a nearby, intense external source of photons is present. With these caveats in mind, and the need to explore further the physics of this "aftermath" part in a self-consistent way, it is clear however that the mechanism described has the potential to produce amounts of lithium comparable to the primordial values as well as to stellar nucleosynthesis and cosmic-ray synthesis. We point out that future population studies should take this mechanism into account.

It is also worth remarking that microquasars are indeed observed in the X-ray bands in our Galaxy, and that in principle their optical and infrared counterparts are observable, giving rise to the possibility of searching for the signature of lithium directly. Alternatively, the gamma-ray lines associated to the production of lithium through $\alpha + \alpha$ reactions could also be looked for, thus opening-up an interesting new target in the X-ray astronomy of local objects. It is thus feasible to check the validity of the mechanism studied here against observations and set constraints on the parameters and nature of the accretion onto stellar mass black holes.

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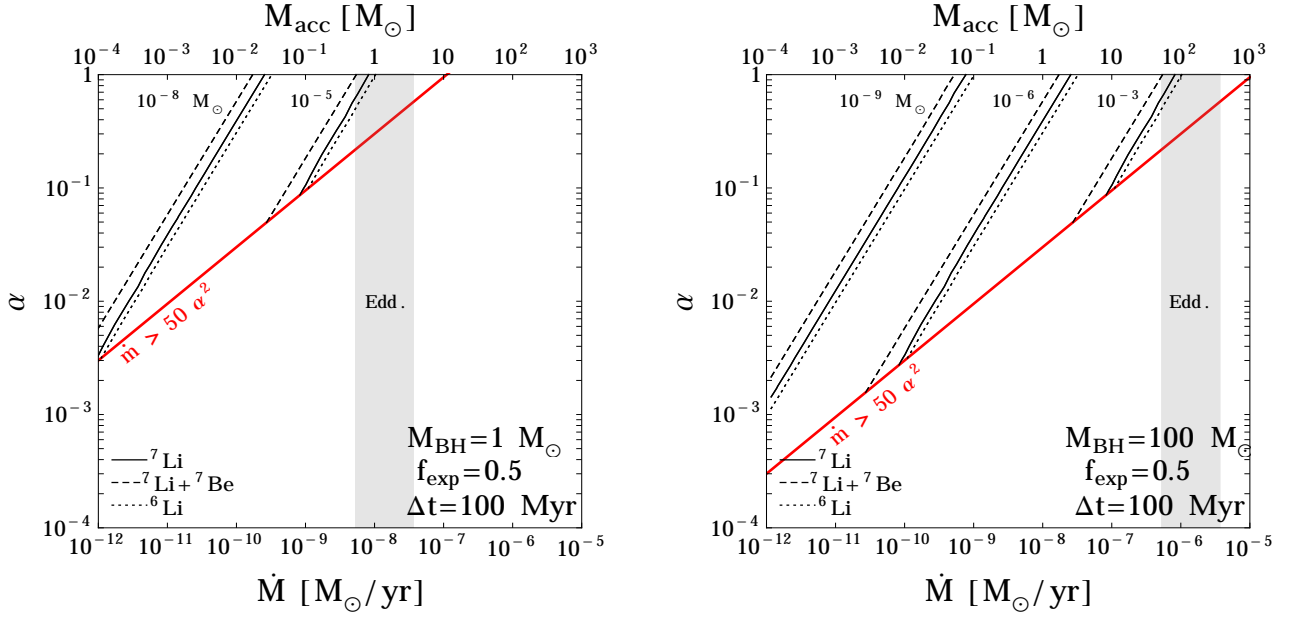
Fig. 1: Contours of the total expelled mass of ^{7}Li (plus ^{7}Be) and ^{6}Li in the parameter space α vs $\dot{M}$ for a black hole of 1 M$_\odot$ (left) and 100 M$_\odot$ (right).

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