21 cm absorption by compact hydrogen discs around black holes in radio-loud nuclei of galaxies

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Abstract. The clumpy maser discs observed in some galactic nuclei mark the outskirts of the accretion disc that fuels the central black hole and provide a potential site of nuclear star formation. Unfortunately, most of the gas in maser discs is currently not being probed; large maser gains favor paths that are characterized by a small velocity gradient and require rare edge-on orientations of the disc. Here we propose a method for mapping the atomic hydrogen distribution in nuclear discs through its 21 cm absorption against the radio continuum glow around the central black hole. In NGC 4258, the 21 cm optical depth may approach unity for high angular resolution (VLBI) imaging of coherent clumps which are dominated by thermal broadening and have the column density inferred from x-ray absorption data, \( \sim 10^{23} \text{ cm}^{-2} \). Spreading the 21 cm absorption over the full rotation velocity width of the material in front of the narrow radio jets gives a mean optical depth of \( \sim 0.1 \). Spectroscopic searches for the 21 cm absorption feature in other galaxies can be used to identify the large population of inclined gaseous discs which are not masing in our direction. Follow-up imaging of 21 cm silhouettes of accelerating clumps within these discs can in turn be used to measure cosmological distances.

Keywords: massive black holes, star formation
1. Introduction

The discovery of an edge-on H$_2$O maser disc in the nucleus of NGC 4258 [1, 2] provides the best current evidence for a nuclear black hole outside the Milky Way galaxy. The radial extent of the maser ring, $\sim$0.14–0.28 pc, and its measured Keplerian rotation profile, between $\sim$770–1100 km s$^{-1}$, imply a central black hole mass $M \approx 4 \times 10^7 M_\odot$ [3]. To obtain large maser gains, any such disc needs to be viewed at a nearly edge-on orientation with the maser clumps lying along the lines of minimal variation in the line-of-sight velocity [4, 5]. Given the small geometric likelihood of edge-on orientations, the subsequent discovery of maser discs in the nuclei of other galaxies [6]–[8] demonstrated that cold nuclear discs must be ubiquitous. The maser clumps potentially mark the outskirts of the accretion disc that fuels the central black hole in these galaxies.

The Milky Way galaxy does not show evidence for a compact nuclear disc but instead features young massive stars at an orbital radius of $\lesssim$0.3 pc from the central black hole, SgrA* [9, 10]. These stars could not have formed in a central molecular cloud because of the strong tidal field of SgrA* [11]. Instead, they are conjectured to have formed in a cold compact disc, at a sub-parsec distance from SgrA*, where the disc self-gravity was important [12]–[14]. For the generic radial profile of a viscous accretion disc, the Toomre Q parameter is indeed expected to approach unity at the required distance scale [15]–[18], making the disc unstable for fragmentation. This coincidence could also explain the clumpy nature of maser discs at a rotation velocity of $\sim$10$^3$ km s$^{-1}$ [14]. Elsewhere in our Galaxy, masers are observed to be associated with regions in which massive stars form [19, 20]. It is therefore likely that the observed maser discs in external galactic nuclei represent sites of star formation [14]. The abundance of maser discs implies that galactic nuclei experience common episodes of disc formation, during which massive stars—like those observed near SgrA*—are born. Winds from these massive stars or supernova explosions (supplemented by additional feedback from the accreting nuclear black hole) could have dispersed the central disc in the Milky Way galaxy on a short timescale of $\lesssim$10$^7$ years. In the future, a new disc might form when fresh cold gas will assemble once again around SgrA*.

Little is known observationally about the global gas distribution in the observed maser discs [3]. Here we propose to spatially map the distribution of atomic hydrogen in nuclear discs through its 21 cm absorption of background radio glow around the black hole [21]. It is known that radio-emitting plumes (which define the base of large-scale jets [30]) exist...
around NGC 4258 (see figure 1 in [3]), but the angular extent of the innermost radio emission at 1.42 GHz and its potential absorption by the disc have not been explored as of yet in the published literature [31]. In section 2 we calculate the expected optical depth for 21 cm absorption in nuclear gaseous discs. This absorption signature could be identified through very long baseline interferometry (VLBI) observations of regions where the continuum backlighting is sufficiently bright.

Hydrogen absorption was already detected spectroscopically in some galaxies that host maser discs (see [22,23] and references therein). In the Gigamaser galaxy TXS2226-184, the 21 cm absorption was spatially resolved on scales of tens of pc [24], well outside the innermost accretion disc of interest here. Extended absorption on large scales was also observed in the cores of other galaxies, such as NGC 4151 [26], Cygnus A [25], NGC 4261 [27], NGC 1068 [28] and 1946+708 [29]. In this paper, we focus on the prospects of imaging the innermost compact disc that feeds the central black hole with gas.

In principle, 21 cm absorption by nuclear discs can be mapped at high angular and spectral resolutions. The velocity and acceleration of clumps within the disc can then be used to infer the angular diameter distance to the sources, as demonstrated for maser clumps in NGC 4258 [2], [32]–[34]. The 21 cm absorption feature can also be searched for spectroscopically (without spatial resolution) in a survey over a large number of compact radio sources. Because the 21 cm absorption signature would appear for arbitrary disc inclination, a dedicated search for this signature would be more likely to find nuclear discs than searches for masers which are limited to edge-on orientations of the discs. Follow-up VLBI imaging of discs could then be used to infer the central black hole mass for a large sample of galaxies.

2. Optical depth of compact nuclear discs

The radiative transfer equation for the intensity $I_\nu$ of the 21 cm line along a particular line-of-sight is [35]

$$\frac{dI_\nu}{ds} = \frac{\phi(\nu) h \nu}{4\pi} \left[n_2 A_{21} - (n_1 B_{12} - n_2 B_{21}) I_\nu\right],$$

(1)

where $\nu$ is the photon frequency, $ds$ is the path element, $\phi(\nu)$ is the line profile function normalized by $\int \phi(\nu) d\nu = 1$ (with an amplitude of the order of the inverse of the frequency width of the line, $\Delta \nu$), subscripts 1 and 2 denote the lower and upper levels of the line, $n$ denotes the number density of atoms at the different levels, and $A$ and $B$ are the Einstein coefficients for the transition between these levels. We make use of the standard relations: $B_{21} = (g_2/g_1) B_{12}$ and $B_{12} = (g_2/g_1) A_{21} n / I_\nu$, where $g$ is the spin degeneracy factor of each state. For the 21 cm transition, $A_{21} = 2.85 \times 10^{-15}$ s$^{-1}$ and $g_2/g_1 = 3$ [36]. The relative populations of hydrogen atoms in the two spin states defines the so-called spin temperature, $T_s$, through the relation, $(n_2/n_1) = (g_2/g_1) \exp \left\{-E/kT_s\right\}$, where $E/k = 0.068$ K is the transition energy. In the regime of interest here, $T_s \gg E$ and so $[(g_2/g_1)(n_1/n_2) - 1] \approx E/kT_s$ and $n_2 \approx 3 n_H$, where $n_H$ is the total number density of hydrogen atoms. Moreover, the brightness of the spontaneous 21 cm emission is too weak to be detectable. We therefore ignore the first term in the square brackets of equation (1) and consider the absorption signature of the gas against a bright radio continuum glow.
in the background. Defining the optical depth along a ray as \( \tau = -\Delta \ln I_\nu \), we get

\[
\tau(\nu) = \frac{3}{32\pi} \frac{h^3 c^2 A_\nu}{E^2} (\nu \phi(\nu)) \frac{N_H}{k T_s},
\]

where \( N_H = \int n_H \, ds \) is the column density of hydrogen.

To get an estimate for the average optical depth value across the line profile, we write \( \phi(\nu) = (\Delta \nu/\nu) \), where \( (\Delta \nu/\nu_0) = (\Delta \nu/c) \) is the fractional Doppler width of the line, corresponding to a velocity spread \( \Delta v \) among the absorbing atoms. The minimum linewidth attainable is dictated by the spread in the thermal velocities of the atoms, for which \([35]_, \Delta v = v_{\text{th}} = (2kT/m_H)^{1/2} \), where \( m_H \) is the hydrogen atom mass. A larger width can be induced by a gradient in the bulk velocity of the gas along the line-of-sight and is calculated in the Sobolev approximation\(^1\). When the 21 cm line is optically thin (\( \tau \ll 1 \)), the absorption signal obtains a width that reflects all the contributing gas elements within the angular resolution and frequency band of the observations.

Substituting all the coefficients into equation (2) yields

\[
\tau = 0.7 \left( \frac{N_H}{10^{23} \text{ cm}^{-2}} \right) \left( \frac{T_s}{8 \times 10^3 \text{ K}} \right)^{-1} \left( \frac{\Delta v}{10 \text{ km s}^{-1}} \right)^{-1}.
\]

The specific numerical values that were substituted on the right-hand side of equation (3) correspond to the expected parameters of the atomic hydrogen disc in NGC 4258 \([3]_\). X-ray observations of this system indicate a hydrogen column density of \( \sim 10^{23} \text{ cm}^{-2} \) \([39]_\). Based on the observed x-ray luminosity of NGC 4258 and the warped geometry of its disc, the gas is expected to be predominantly atomic (rather than molecular) outside a radius \( \sim 0.3 \text{ pc} \) (see figure 23 in \([3]_\)). Theoretical calculations \([5]_\) suggest that the atomic hydrogen\(^2\) in the disc of NGC 4258 has an asymptotic temperature \( \sim 8000 \text{ K} \), providing a thermal velocity width of \( v_{\text{th}} \approx 10 \text{ km s}^{-1} \). At the high densities under consideration, we assume that the spin temperature \( T_s \) is in collisional equilibrium with the kinetic temperature of the gas. High resolution imaging of nuclear discs can therefore be used to constrain their density and temperature distributions through equation (3).

The scale height of a thin accretion disc, \( h \), is expected \([40]_\) to be a fraction \( \sim (v_{\text{th}}/v_\phi) \) of its radius \( r \), where \( v_\phi(r) = (GM/r)^{1/2} \) is the rotation speed at \( r \) for a black hole mass \( M \). A line-of-sight which crosses the disc at an angle \( \theta \) relative to the normal to the disc samples a spread in the line-of-sight bulk velocity that is \( \leq (2h/\cos \theta)[(dv_\phi/dr) \sin \theta] = (\sin^2 \theta/\cos \theta) v_{\text{th}} \). For the warped (bowl-shaped) maser region of NGC 4258, the value of \( \cos \theta \approx 0.3 \) \([3]_\) yields \( \Delta v \approx (1-3) \times v_{\text{th}} \).

In order for VLBI imaging to reach the thermal broadening minimum of \( \Delta v \), a particular spatial resolution element needs to be dominated by a single clump of gas with a coherent bulk velocity. Such a clump would have a small line-of-sight bulk velocity if it is located in front of the black hole and up to the full rotation speed on the side. If the clump fills only a fraction \( f \) of the source area within the resolution element, then \( \tau \) will be reduced by a factor of \( f \). For the diffuse gas in the disc, the spatial resolution

\(^1\) In the Sobolev approximation \([37]_\), the term \( \nu \phi(\nu)N_H \) in equation (2) is replaced by \( c n_H/(dv_\phi/ds) \), where \( dv_\phi/ds \) is the line-of-sight gradient of the line-of-sight velocity of the gas. In the cosmological context of 21 cm absorption by a uniform intergalactic medium which encounters Hubble expansion, this gradient is simply the Hubble parameter (see, e.g., \([38]_\)).

\(^2\) The molecular gas in the disc is cooler \( (\sim 10^3 \text{ K}) \) and could potentially be probed through other absorption lines.
required to achieve the thermal width minimum is of the order of the disc scale height, \( h \sim (v_{th}/v_\phi)r \). This resolution scale corresponds to \( \sim 10^{-2}r \sim 3 \times 10^{-3} \) pc for NGC 4258. At a wavelength of 21 cm and a source distance of 7.2 Mpc, this resolution requires an unrealistic baseline of \( \sim 5 \times 10^5 \) km, larger by a factor of 40 than the diameter of the Earth. Thus, a terrestrial VLBI will resolve the disc in NGC 4258 only around and outside the maser region (\( r \gtrsim 0.14 \) pc). Coincidentally, this is indeed the region expected to be dominated by atomic hydrogen [3]. An analogous disc around a quasar black hole whose mass \( M \) is larger by two orders of magnitude than in NGC 4258, could in principle be resolved out to a distance of \( \sim 1 \) Gpc.

We conclude that the high value of the optical depth in equation (3) applies to silhouettes of coherent clumps in which thermal broadening dictates the velocity spread \( \Delta v \). Such clumps are expected to exist outside the maser region, where the Toomre \( Q \) parameter is of order unity or lower [14]. If individual clumps of atomic hydrogen are not resolved or if the disc is smooth, then the optical depth would be diluted over a broader velocity width. In general, the absorption depth at a given frequency bin scales as the fractional (brightness-weighted) area of the continuum source over which hydrogen atoms resonate with photons in the observed frequency bin.

Under a uniform background illumination, the absorption spectrum of an unresolved circular disc can be obtained through a sum over concentric rings in the disc plane. We assume that the normal to the disc plane is inclined at an angle \( \theta \) relative to the line-of-sight. A single optically thin ring with a circular rotation velocity \( v_\phi(r) = (GM/r)^{1/2} \) and a radius \( r \) gives a U-shaped spectral profile in terms of \( -1 < \delta/\nu < 1 \) [41]:

\[
\tau(\nu, r) = \frac{\tau_{\text{ring}}(r)}{\pi(1 - \delta^2)^{1/2}},
\]

where \( \delta = [(\nu - \nu_0)/\nu_0]/[0.5\Delta v/c], \Delta v = 2v_\phi(r)\sin \theta \) and

\[
\tau_{\text{ring}}(r) = 0.44 \times 10^{-2} \left( \frac{N_\text{H}(r)}{10^{23} \text{ cm}^{-2}} \right) \left( \frac{T_\text{s}}{8 \times 10^4 \text{ K}} \right)^{-1} \left( \frac{v_\phi(r)\sin \theta}{800 \text{ km s}^{-1}} \right)^{-1}.
\]

The total absorption feature of an unresolved disc can be obtained by summing over all the rings in which atomic hydrogen resides, weighted by the brightness distribution of the backlighting at \( \nu_0 = 1.42 \) GHz.

For an arbitrary background illumination, the net deficit in the fractional spectral intensity across the area \( S \) of an unresolved optically thin source is given by

\[
\frac{\Delta I_S(\nu)}{I_S} = -\int_S I_\nu(x,y)\tau(\nu, x, y) \, dx \, dy / \int_S I_\nu(x,y) \, dx \, dy,
\]

where \( (x, y) \) are the sky coordinates and the unabsorbed continuum source can be assumed to have a smooth (typically power law, \( I_\nu \propto \nu^\alpha \)) spectrum across the absorption line profile in the numerator. For a thin disc which is not perfectly edge-on, the exact expression for the optical depth \( \tau(\nu, x, y) \) in equation (2) can be approximated as the thermally broadened value in equation (3) at the Doppler shifted frequency \( \nu_0[1 - v_\parallel/c] \), where \( v_\parallel(x, y) \) is the line-of-sight component of the bulk velocity of the gas. Clearly, in order for the spectral deficit to be noticeable, a dominant component of the radio emission needs to originate behind the absorbing disc. If the background illumination originates from a narrowly collimated jet (as indicated by the 22 GHz image of NGC 4258), then the
absorption feature will be characterized by the low line-of-sight velocity spread ($\Delta v$) of the material in front of the jet. In this case, the spectral deficit will be larger than the deficit associated with the full velocity spread of the disc. For the narrow jets of NGC 4258 [3], we estimate $\Delta v \sim 100$ km s$^{-1}$ and $\tau \sim 0.1$. A dedicated search for the 21 cm spectroscopic feature in other compact radio sources can be used to identify new nuclear discs in distant galaxies.

The proposed studies require the presence of a compact emission region for the radio source. Such a region is known to exist in $\lesssim 10\%$ of all active galactic nuclei [42]. Previous studies of 21 cm absorption in compact radio cores (such as the COINS sample [43]) have identified 21 cm optical depth values of up to $\tau \sim 0.44$, demonstrating the feasibility of the measurements proposed here.

3. Discussion

The parameters of the maser disc in NGC 4258 imply that atomic hydrogen within the compact gaseous discs in galactic nuclei can produce measurable 21 cm absorption against the back light of continuum radio emission around the central black hole. For NGC 4258, the 21 cm optical depth may approach unity in silhouettes of coherent clumps which are dominated by thermal broadening and have the column density inferred from x-ray absorption data [39]. Spreading the absorption across the rotation velocity width of the material in front of the collimated jets in NGC 4258 results in an expected optical depth of $\sim 0.1$.

More than half of all nuclear H$_2$O megamasers show x-ray absorption with column densities $N_H \sim 10^{24}$–$10^{25}$ cm$^{-2}$ (see [44] and figure 7 in [45]), at which the optical depth for 21 cm absorption might exceed unity. High resolution VLBI images of 21 cm absorption can be used to map the distributions of the density, temperature and line-of-sight velocity of atomic hydrogen in nuclear discs. Such maps could show direct evidence for spiral arms [46], which are conjectured to exist based on the latest maser data in NGC 4258 [2,34]. The spiral perturbations to the smooth density and rotation velocity profiles of the disc would show up only if the background radio illumination would cover a substantial portion of the disc (i.e. the base of the jet is broad). More generally, the absorption maps hold the potential for testing current models of accretion discs, shedding light on the geometry of obscured (Compton-thick) quasars and improving our understanding of star formation in galactic nuclei.

A comprehensive search for a spectroscopic absorption feature in radio-loud nuclei of galaxies can be used to find a large number of inclined gaseous discs which are not masing in our direction. The improved statistics of known nuclear discs would provide better understanding of the duty cycle of black hole fueling and star formation in galactic nuclei.

Remote atomic hydrogen within the host galaxy would also result in absorption but will be limited to low-velocity widths. The compact nuclear disc is expected to dominate the wings of the 21 cm absorption profile which extend out to velocity offsets of $\pm 10^3$ km s$^{-1}$. Follow-up imaging of the nuclear disc can be used to separate out extended galactic absorption. The innermost disc is expected to show a thin geometry and large rotation speeds that distinguish it from the outer gas. Since the Toomre $Q$ parameter of a standard accretion disc approaches unity at rotation velocities of thousands of km s$^{-1}$, the outer edge of the smooth accretion disc is physically small for low-mass black holes.
In order to be able to resolve the disc, the source needs to be nearby or the black hole needs to be very massive.

VLBI measurements of the velocity and acceleration of coherent hydrogen clumps within the disc can be used to infer the angular diameter distance to the source, as demonstrated with maser clumps [2], [32]–[34]. Detection of suitable radio sources out to sizeable redshifts could potentially place new constraints on the equation of state of the dark energy through the dependence of the angular diameter distance on source redshift [32].

The proposed observations are challenging but potentially feasible for sufficiently bright sources using existing VLBI telescopes. However, the promise of this method will be fully realized with the planned square kilometer array (SKA)\(^3\). The SKA will be sensitive to absorption at extremely low optical depths (down to \(\tau \sim 10^{-2}\) for sources of a few mJy) and will facilitate the serendipitous detection of hydrogen absorption from numerous galaxies in any observed field [23, 47].

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\(^3\) [http://www.skatelescope.org/](http://www.skatelescope.org/)
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