Cosmic compass - First tomography of an outer 3D sub-Gauss field via atomic alignment

Heshou Zhang\textsuperscript{1,2}, Manuele Gangi\textsuperscript{3}, Francesco Leone\textsuperscript{4}, Andrew Taylor\textsuperscript{1}, Huirong Yan\textsuperscript{1,2}\textsuperscript{*}

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Sub-Gauss magnetic fields are crucial for many physical processes from Galactic kpc scale to stellar Au scale, but are nontrivial to detect. All present magnetic diagnoses trace only one component of a magnetic field at best\textsuperscript{[1]}. Here we report the first observational results that unveil 3D topology as well as the strength of a sub-milliGauss magnetic field beyond our solar system. We found that two weak neutral iron absorption lines from the ground state in the atmosphere of 89 Her produced counterintuitive high-amplitude polarizations and consistent polarization angles, exactly in line with the theoretical prediction from ground state alignment (GSA)\textsuperscript{[2]}. Our analysis reveals the first sub-AU scale magnetic field on 89 Her, that is 1.3kpc away, has a 3D orientation aligned to the stellar outflow axis and a strength of $70\mu G \lesssim B \lesssim 150\mu G$, thus substantially improving the accuracy by five orders of magnitude compared to the previous $10G$ upper limit set by

\textsuperscript{[1]}Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, D-15738 Zeuthen, Germany. \textsuperscript{[2]}Institut für Physik und Astronomie, Universität Potsdam, Haus 28, Karl-Liebknecht-Str. 24/25, D-14476 Potsdam, Germany. \textsuperscript{[3]}INAF - Osservatorio Astrofisico di Catania, Via S. Sofia 78, I-95123 Catania, Italy \textsuperscript{[4]}Università di Catania, Dipartimento di Fisica e Astronomia, Sezione Astrofisica, Via S. Sofia 78, I-95123 Catania, Italy. \textsuperscript{*}Corresponding author: huirong.yan@desy.de.
non-detection of Zeeman effect\textsuperscript{3}. This long-awaited discovery is anticipated to usher in a new era of precise measurement of sub-gauss magnetic field in the Universe.

Magnetic field is ubiquitous in the Universe. Despite its importance, observational studies of sub-Gauss magnetic field are still very limited, particularly in diffuse medium. The Zeeman splitting samples only relatively strong magnetic fields in dense and cold clouds\textsuperscript{4}. There is no universal magnetic tracer for sub-Gauss magnetic field in diffuse medium beyond our solar system. Even estimation of one component of magnetic field, i.e., the line-of-sight or plane-of-sky projection, is considered significant. Therefore it is important to search for novel magnetic tracers taking advantage of current facilities\textsuperscript{5–8}. While the Zeeman effect is centred about energy splitting, angular momentum redistribution is the only effect for atomic systems in weak magnetic fields and thus provides exclusive information on sub-Gauss magnetic fields. It was predicted a decade ago that polarization of absorption lines arising from Ground State Alignment can be a universal magnetic tracer for sub-Gauss magnetic fields as well as a direct tool for 3D magnetic field topology\textsuperscript{2}. In contrast to grain alignment, GSA is an established physical phenomenon which has solid physical foundations and has been studied and supported by numerous experiments\textsuperscript{9–13}. The alignment is in terms of the angular momentum of atoms and ions (hereafter “atoms” for simplicity). The optical pumping by anisotropic radiation aligns atoms by transferring the angular momentum from photons\textsuperscript{14–16}. The atoms are magnetically realigned by fast precession as long as the Larmor precession rate $\nu_L$ is larger than the pumping rate $\nu_R$. The alignment is particularly suitable for weak sub-Gauss magnetic field since atoms have long life time in their ground states\textsuperscript{21}. The resulting absorption lines from the aligned atoms/ions are polarized parallel or perpendicular to the magnetic field direction depending on the angle between the symmetry axis of the radiation and the magnetic field. In this letter, we report the first observational evidence of GSA, with which we demonstrate that GSA is a powerful tool in tracing sub-Gauss magnetic field with current facilities.

The object is the photosphere of the post-AGB binary star 89 Her, a binary system 1.3\textit{kpc} away. Its magnetic field, although believed to be a crucial shaping factor for subsequent phases
Figure 1 | 3D topology of 89 Her post-AGB binary system. The system is plotted from two different orientations showing the line-of-sight and plane-of-sky projections. The orbital phases are marked on the secondary track. The color scale indicates the line-of-sight velocity ($v_z$) of the medium. The absorption lines are composed of the blue-/red-shifted components contaminated by the stellar outflows and the relatively clean rest-frame component. The plane-of-sky projection of the symmetric axis of the outflow is $45^\circ$ to the East-West direction. The resulting 3D magnetic field directions for different orbital phases are displayed.
Table 1 | Physical parameters. The effective temperature $T_{\text{eff}}$, surface gravity $\log g$, the metallicity are listed\textsuperscript{18, 19}. $\tau_h$ indicates the photospheric height at which the lines studied here are formed.

| Sp. Type   | $T_{\text{eff}}[K]$ | $\log g$ | $Fe/H$ | $R[R_\odot]$ | $\tau_h[R_\odot]$ |
|------------|---------------------|----------|--------|--------------|-------------------|
| Primary F2Ibp | 6500                | 0.5 $\sim$ 1.0 | $-0.5$ | 41          | 3.8 $\sim$ 12.6   |
| Secondary M0V | 4045                | 4.7      |        | 0.6         |                   |

of planetary nebulae, remains unknown. Earlier attempts with current magnetic tracers have failed to produce any measurables: no continuum polarization is detected (grain alignment is not applicable here), no circular polarization is observed (which means Zeeman splitting is negligible and thus leads to a 10G upper limit). The linearly polarized spectra of 89 Her are taken from archive data of the ESPaDOnS spectropolarimeter\textsuperscript{5}. The atmospheric parameters and the logbook of observations of the system are given in Table 1 and Extended Data Table 1, respectively. The photospheric absorption lines are identified with a synthetic spectrum computed by SYNTHE\textsuperscript{20}. The absorption lines have two components: the rest-frame absorption component arising from the photosphere of the primary; and the red-/blue-shifted wing components strongly influenced by the emission from the polar outflow, which is $\sim 12^\circ$ from line of sight (see Figure 1). The polarization angles of 960 absorption lines show variability correlating with the secondary orbital phase, i.e., orthogonal to the primary secondary orientation, consistent with expectations from optical pumping (see Figure 2a)\textsuperscript{3}. These are all strong absorption lines (with optical depth $\tau \gtrsim 0.6$) from transitions among excited states.

Here we focus on the rest-frame component of photospheric lines. The absorption lines are weak with $\tau < 0.5$ and therefore were not studied before. Two Fe I and three Ti I absorption lines from the ground states are identified with clear polarization signals (see Extended Data Table 1 for details). The polarizations of all these five lines differ from the optical pumping direction by $5\sigma$ (see Figure 2 and Extended Data Tables 2 & 3). The results for the five absorption
lines unambiguously point to the magnetic precession as the primary cause for the deviation of polarization angles from the radiation directions. In particular, the polarization directions of the two Fe I remain unchanged through the secondary orbital phases, as shown in Figure 2b. Given the much longer lifetime of the atoms in the ground states, the only explanation to this intriguing phenomenon is that the magnetic precession dominates the photo-excitation rate in the ground states and therefore the polarization of these ground-state absorption lines unveils the magnetic field direction. This is the first observational evidence of GSA effect in the Universe.

Depending on the relative magnetic field strength, the magnetic influence on the ground state can be divided into two regimes\(^{21}\): GSA regime (\(\nu_L \ll \nu_R\)), where the magnetic precession dominates over optical pumping and the polarization direction follows magnetic field direction; and ground level Hanle effect (\(\nu_L \sim \nu_R\)), where the magnetic precession rate is comparable to the optical pumping and the resulting polarization differs from either the optical pumping regime or GSA regime. The magnetic field strength in different regimes is compared to the optical pumping rates of the five absorption lines in Figure 3. The pumping rates are obtained by analyzing the pumping condition in the extended radiation field of 89 Her (see Table 1\(^{22}\). The three Ti I lines are in ground-level Hanle regime because their polarization angles are different from either case of the optical pumping and the magnetic alignment, as shown in Extended Data Table 3. The lower and upper limits of magnetic field strength are thus obtained, \(70 \mu G \lesssim B \lesssim 150 \mu G\). The accuracy is increased by five decades compared to the previous 10 G upper limit constrained by non-detection of the Zeeman effect.

The two magnetically aligned Fe I lines are further analyzed to acquire the magnetic field topology. The polarization directions of the two lines are aligned within 3\(\sigma\) error through all orbital phases, in line with theoretical expectation (see Figure 2b and Methods). Furthermore, the 90° degeneracy is removed and the magnetic field is found to be parallel to the polarization direction, based on the comparison between observed degree of polarizations of the two Fe I lines and theoretical predictions (Methods). For multiplets arising from the same ground sub-level, the third dimension, i.e., the angle between the magnetic field and line of sight, can be
Figure 2 | Polarization angles and inferred direction of magnetic from the line of sight.
(a) 960 strong absorption lines from excited states, the polarization angle ($\xi_r$) is parallel to the optical pumping direction, synchronized with orbital phases; (b) the Fe I polarization angles ($\xi_{FeI}$), which are magnetically aligned; (c) The resulting line-of-sight angle $\theta_B$. The error bars indicate the 3$\sigma$ uncertainty range on the measurement.
Figure 3 | magnetic field strength analysis. $x - axis$ is the pumping rate $\nu_R$, $y - axis$ is magnetic field strength. There are different polarization regimes according to the relative magnetic field strength. The pumping rates in 89 Her for the five ground level absorption lines are marked on the top. The dash-dotted line shows the lower limit of magnetic field strength above which magnetic precession has influence on all the five lines. The two Fe I lines reside completely in GSA regime. The dotted line marks the upper limit set from the fact that all the three Ti I lines reside in Ground level Hanle regime.
generically expressed as:

$$\sin^2 \theta_B = \begin{cases} 
\frac{2c_1c_2(\omega u_2 - \omega u_1)}{3(c_1c_2(\omega u_2 - \omega u_1) \pm (c_1\omega u_2 - c_2\omega u_1))}, & \text{sgn}(\omega u_1) = \text{sgn}(\omega u_2) \\
\frac{2c_1c_2(\omega u_2 - \omega u_1)}{3(c_1c_2(\omega u_2 - \omega u_1) \mp (c_1\omega u_2 + c_2\omega u_1))}, & \text{sgn}(\omega u_1) = -\text{sgn}(\omega u_2) 
\end{cases}$$

where $c_1, c_2$ are directly related to the degrees of polarization and optical depths of a doublet as shown in Equation (9) in Methods. Accordingly, the 3D magnetic field topology of 89 Her is retrieved (see Figure 1).

Our results unambiguously disclose the first observational signature of GSA. This has allowed a direct determination of 3D field detection as well as its strength. The signal-to-noise ratio for the spectro-polarimetry of these ground-state absorption lines in this study can be achieved with reasonable exposure time by various existing observational instruments across the world, e.g., PEPSI, HARPS, HANPO. Our study offers the direct observable to fill in the long standing vacancy of the sub-Gauss magnetic field diagnoses that can be widely applied to multiple phase medium with radiation dominated excitations. GSA can be implemented with multi-frequency data ranging from UV to submillimeter to trace not only the spatial but also the temporal variations of magnetic field.\textsuperscript{23, 24} This detection marks the onset of a new era in high-precision magnetic fields detection in deep universe and is expected to exponentially increase our knowledge on interstellar magnetism.

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Methods  Observational data

Observed spectra consist of Stokes $I$, $Q$, $U$ and null $NQ$, $NU$. The null spectra control the presence of spurious contributions resulting from observations or from the data reduction procedure. Spectra are corrected for Doppler shift due to the orbital motion of the primary component. Stokes $I$ is normalized to the local continuum. From Stokes $Q$ and $U$, the polarization $P$ is computed:

$$P = \sqrt{(Q/I)^2 + (U/I)^2}, \quad (2)$$

the null polarization $NP$:

$$NP = \sqrt{(NQ/I)^2 + (NU/I)^2}, \quad (3)$$

and the polarization angle $\xi$:

$$\xi = \frac{1}{2} \arctan \left( \frac{U}{Q} \right) + \xi_0 \quad (4)$$

with:

$$\xi_0 = \begin{cases} 
0 & \text{if } Q > 0 \text{ and } U \geq 0 \\
\pi & \text{if } Q > 0 \text{ and } U < 0 \\
\frac{\pi}{2} & \text{if } Q < 0
\end{cases} \quad (5)$$

for $Q \neq 0$. For $Q = 0$:

$$\xi = \begin{cases} 
\frac{\pi}{4} & \text{if } U > 0 \\
\frac{3\pi}{4} & \text{if } U < 0.
\end{cases} \quad (6)$$

Thus the mean and variance of the noise are provided by the Null spectrum of the lines. We analyzed the confidence level of the detected lines based on the PDF of signal $P$. The results are presented in Extended Data Table 1.

**Line-of-sight magnetic angle analysis**

In earlier observational studies the polarization degree of atomic lines is only used to calculate the confidence level of the detection of polarization, as demonstrated in the previous
paragraph. Since more than $3\sigma$ detection of polarization are found in all cases for both of the Fe I lines, the polarization degrees actually provide a wealth of information in GSA. Its line by line property is predictable from their different electron configurations (see Extended Data Figure 1). Particularly if two lines among multiplets from the same ground level are observed, the magnetic field direction along the line of sight can be precisely obtained. The theoretical Stokes parameters $[\tilde{I}, \tilde{Q}, \tilde{U}, \tilde{V}]$ are defined with $\tilde{Q}$ measured from the magnetic field direction on the plane of sky. They are given by:

\[
\tilde{I} = (I_0 + Q_0)e^{-\tau(1+\eta_1/\eta_0)} + (I_0 - Q_0)e^{-\tau(1-\eta_1/\eta_0)},
\]

\[
\tilde{Q} = (I_0 + Q_0)e^{-\tau(1+\eta_1/\eta_0)} - (I_0 - Q_0)e^{-\tau(1-\eta_1/\eta_0)},
\]

\[
\tilde{U} = U_0e^{-\tau}; \tilde{V} = V_0e^{-\tau},
\]

where $[I_0, Q_0, U_0, V_0]$ are the Stokes parameters of the background emission, which is unpolarized in the case of 89 Her. $\tau \equiv 1 - I/I_C$ is the optical depth of the line. $\eta_i$ are absorption coefficients of the Stokes parameters. The ratio of $c \equiv \eta_1/\eta_0$ is given by:

\[
c = -\frac{1.5\sigma_0^2(J_l)\sin^2\theta_B\omega_{J_lJ_u}^2}{\sqrt{2 + \sigma_0^2(J_l)(1 - 1.5\sin^2\theta_B)\omega_{J_lJ_u}^2}},
\]

where $\sigma_0^2(J_l)$ is the alignment parameter on the lower level. For multiplets absorption lines from the same ground level, it is solely dependent on the sign of $\omega_{J_lJ_u}^2$ whether the polarization is parallel or perpendicular to the magnetic field direction. $\theta_B$ is the angle between magnetic field and the line of sight.

\[
\omega_{J_lJ_u}^2 \equiv \begin{cases} 1 & 1 & 2 \\ J_l & J_l & J_u \end{cases} / \begin{cases} 1 & 1 & 0 \\ J_l & J_l & J_u \end{cases},
\]

is determined by the electron configurations of the transition $J_l \rightarrow J_u$. From Equation (7), the ratio $c$ can be expressed by the observables:

\[
|c| = \frac{1}{2\tau} \ln \left( \frac{1 + P}{1 - P} \right),
\]

where the degree of polarization $P$ is defined in Equation (2).
The alignment parameter is the same for two transitions with the same ground level ($J_l \rightarrow J_{u1}$, $J_l \rightarrow J_{u2}$, with the configuration parameters $\omega_{u1}, \omega_{u2}$). Therefore, the generic expression for the angle between line of sight and magnetic field $\theta_B$ is obtained in Equation (1). In our analysis, the two Fe I absorption lines, whose transitions have different angular momentum configurations Fe I λ5060 (4-3), Fe I λ5166(4-5), are from the same level in the ground state therefore bearing the same alignment parameter. The configuration parameters of these two transitions are of the same sign: $\omega_{u1} = \omega_{u3}^2 = 0.4432; \omega_{u2} = \omega_{u5}^2 = 0.2256$. Therefore, the related results are:

$$\sin^2 \theta_B = \frac{-0.1451c_1c_2}{-0.4352c_1c_2 + \text{sgn}(\sigma_0^2(J_l))(0.2256c_1 - 0.4432c_2)},$$

which satisfies the following conditions:

$$0 \leq \sin^2 \theta_B \leq 1,$$

$$0 \leq |\sigma_0^2(J_l)| \leq 1.$$  

The resulting $\theta_B$ and their 3σ variations in different phases are shown in Extended Table 2. The positive and negative sign of $\sigma_0^2(J_l)$ correspond to the plane-of-sky magnetic field projection parallel or perpendicular to the observed polarization. This 90° degeneracy is further discussed in the next paragraph.

**Break the 90° degeneracy**

We obtain the value ranges of $c_1, c_2$ by considering the 3σ fluctuation introduced by the Null signals. These value ranges are compared with the theoretical expectation of $c_1, c_2$ from Equation (11). The 90° degeneracy can be broken based on the comparison at the phase 0.988. As demonstrated in Extended Data Figure 2, the 3σ value range rectangle is only acceptable for the case $\sigma_0^2(J_l) > 0$, i.e., $B_\perp \parallel \xi_{FeI}$. In addition, the resulting polarization angles of Fe I lines are within 21° for all orbital phases (see Figure 2). The photospheric medium of 89 Her is axially symmetric and stable. Indeed, no significative variability in the equivalent widths of the line profiles is found from earlier study. The field line is therefore unlikely to abruptly change its orientation by $\gtrsim 69°$ from phase to phase. We conclude that the plane-of-sky magnetic direction is parallel to the polarization direction throughout all the orbital phases.
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Extended Data Table 1 | Logbook of observations. Column 1 gives the heliocentric julian data, column 2 provides the corresponding orbital phases. The latter are calculated on the basis of ephemeris determined by\[15\]: $JD(RV_{max}) = 2446013.72(\pm16.95) + 288.36(\pm0.71)$ days. The 3rd to 7th columns list the sigma levels of the polarization signals for the Fe I and Ti I ground level absorption lines.

| HJD      | phase | Fe I 5060Å | Fe I 5166Å | Fe I 5009Å | Ti I 5192Å | Ti I 5426Å |
|----------|-------|------------|------------|------------|------------|------------|
| 54954.125 | 0.004 | 15.4       | 14.2       | 5.3        | 9.6        | 7.9        |
| 54955.849 | 0.01  | 13.8       | 10.5       | 6.6        | 5.4        | 1.7        |
| 54958.121 | 0.018 | 15.2       | 16.2       | 4.8        | 7.0        | 3.5        |
| 54959.874 | 0.021 | 5.5        | 7.2        | 6.4        | 9.2        | 3.2        |
| 53604.753 | 0.325 | 13.3       | 22.4       | 4.5        | 2.5        | 5.8        |
| 55109.823 | 0.544 | 13.4       | 9.1        | 5.9        | 3.9        | 4.1        |
| 53961.777 | 0.564 | 14.8       | 25.4       | 11.4       | 11.3       | 5.3        |
| 53775.115 | 0.916 | 11.8       | 14.3       | 3.7        | 4.6        | 3.0        |
| 53777.096 | 0.922 | 23.5       | 20.1       | 11.5       | 12.9       | 6.2        |
| 55229.169 | 0.958 | 14.9       | 13.0       | 10.6       | 9.3        | 2.9        |
| 54372.821 | 0.988 | 20.6       | 29.8       | 11.4       | 8.7        | 4.3       |
Extended Data Figure 1 | Schematics of the optical pumping and magnetic realignment in GSA regime. Rectangles with circles represent the energy state occupied by atoms. The arrows are the angular momentum of the atoms. The ground state is magnetically aligned, indicating the magnetic precession rate is faster than the optical pumping rate. The excited states are only radiative aligned, indicating the escaping rates from such states are faster than the magnetic precession rate.
Extended Data Figure 2 | Breaking 90° degeneracy. The 3σ ranges of $c_1, c_2$ in the orbital phase 0.988 are compared with the acceptable domains for (a) $\sigma_0^2 > 0$ (b) $\sigma_0^2 < 0$, respectively.
Extended Data Table 2 | Polarization angles $\xi_{\text{Fe}I}$ and resulting $\theta_B$ as well as their standard deviations for Fe I lines 5009, 5192, 5426 Å.

| HJD phase | $\xi_{\text{Fe}I}$ | $\Delta \xi_{\text{Fe}I}$ | $\xi_{\text{Fe}I}$ | $\Delta \xi_{\text{Fe}I}$ | $\theta_B$ | $\Delta \theta_B$ |
|-----------|-------------------|----------------|-------------------|----------------|-------------|-------------|
| 54954.125 | 0.004             | 40.1°          | 3.2°              | 34.8°          | 3.0°        | 30.3°       | 4.3°        |
| 54955.849 | 0.01              | 45.1°          | 3.2°              | 45.0°          | 4.1°        | 32.2°       | 3.3°        |
| 54958.121 | 0.018             | 41.5°          | 2.9°              | 35.5°          | 2.6°        | 31.8°       | 3.9°        |
| 54959.874 | 0.021             | 48.0°          | 6.9°              | 42.9°          | 6.7°        | 32.4°       | 3.9°        |
| 53604.753 | 0.325             | 32.2°          | 6.1°              | 29.2°          | 3.3°        | 25.3°       | 2.7°        |
| 55109.823 | 0.544             | 48.4°          | 4.7°              | 57.5°          | 3.9°        | 27.7°       | 2.7°        |
| 53961.777 | 0.564             | 48.5°          | 4.0°              | 59.4°          | 2.3°        | 22.9°       | 2.3°        |
| 53775.115 | 0.916             | 32.5°          | 4.0°              | 31.9°          | 4.0°        | 32.7°       | 3.4°        |
| 53777.096 | 0.922             | 27.9°          | 2.3°              | 29.3°          | 2.2°        | 26.5°       | 1.7°        |
| 55229.169 | 0.958             | 28.2°          | 4.1°              | 30.5°          | 2.6°        | 26.2°       | 2.7°        |
| 54372.821 | 0.988             | 38.3°          | 1.9°              | 40.0°          | 1.6°        | 25.1°       | 0.1°        |
Extended Data Table 3 | Polarization angles as well as their standard deviations for Ti I lines 5009, 5192, 5426Å

| HJD    | phase | $\xi_{Ti}$ 5009Å | $\Delta \xi_{Ti}$ 5009Å | $\xi_{Ti}$ 5192Å | $\Delta \xi_{Ti}$ 5192Å | $\xi_{Ti}$ 5426Å | $\Delta \xi_{Ti}$ 5426Å |
|--------|-------|------------------|--------------------------|------------------|--------------------------|------------------|--------------------------|
| 54954.125 | 0.004 | 26.7°            | 21.3°                    | 147.5°           | 44.7°                    | 41.0°           | 21.4°                    |
| 54955.849 | 0.01  | 20.1°            | 20.1°                    | 29.8°            | 37.8°                    | 20.2°           | 33.3°                    |
| 54958.121 | 0.018 | 40.2°            | 35.5°                    | 178.9°           | 35.9°                    | 4.4°            | 36.9°                    |
| 54959.874 | 0.021 | 169.1°           | 32.1°                    | 143.9°           | 43.3°                    | 32.7°           | 27.3°                    |
| 53604.753 | 0.325 | 85.1°            | 45.9°                    | 104.4°           | 30.6°                    | 48.2°           | 24.6°                    |
| 55109.823 | 0.544 | 26.3°            | 28.2°                    | 37.0°            | 33.9°                    | 1.2°            | 31.4°                    |
| 53961.777 | 0.564 | 18.2°            | 9.9°                     | 4.3°             | 33.4°                    | 14.4°           | 27.9°                    |
| 53775.115 | 0.916 | 20.7°            | 26.6°                    | 18.0°            | 31.8°                    | 31.5°           | 27.0°                    |
| 53777.096 | 0.922 | 37.4°            | 18.0°                    | 38.0°            | 17.7°                    | 34.9°           | 23.0°                    |
| 55229.169 | 0.958 | 10.3°            | 20.9°                    | 28.0°            | 15.9°                    | 1.1°            | 34.3°                    |
| 54372.821 | 0.988 | 23.8°            | 13.9°                    | 137.9°           | 36.0°                    | 8.8°            | 31.3°                    |